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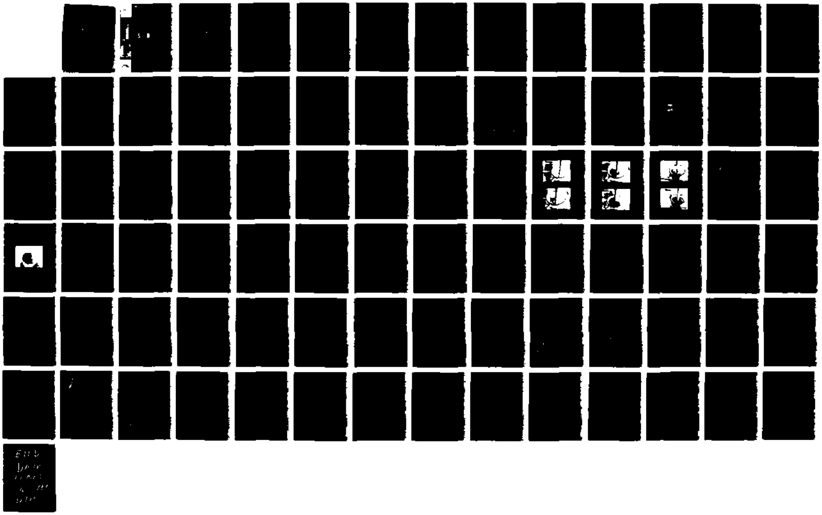

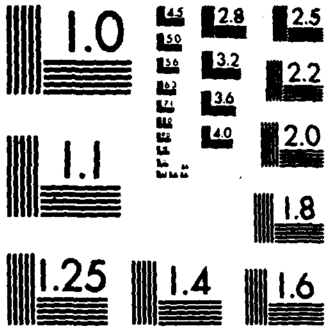

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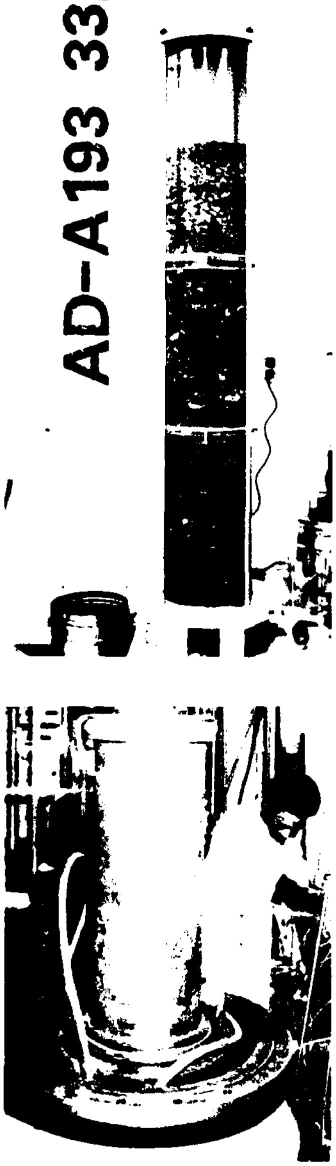

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DEVELOPMENT OF A LABORATORY TEST TO IDENTIFY THE SCOUR POTENTIAL OF SOILS AT PILES SUPPORTING OFFSHORE STRUCTURES

by

Shin-Tower Wang, Lymon C. Reese

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The University of Texas at Austin
Austin, Texas 78712

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This report describes the development of a test to investigate the scour potential of soils at the interface of piles that support offshore structures. These soils are subjected to cyclic loading due to wave action. The test is called the Pile-Soil Scour Potential Test (PSSP). The mechanism of scour around the pile-soil interface is discussed. Due to the complicated interactions between pile, soil, and fluid at the interface, this study is primarily directed toward an experimental approach. In addition to the use of the PSSP test, the existing pinhole test was used to study the scour potential of various soils.

A series of PSSP tests were conducted for examining the scour resistance of soils. The influences of variables such as soil properties, loading frequency, pile diameter, and duration in the scour process were studied by use of the PSSP test.

The most significant findings of these tests are analyzed. A method of predicting the scour potential is suggested and further studies are recommended to improve the method.

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PREFACE

This study was performed by the Geotechnical Engineering Center, Bureau of Engineering Research, The University of Texas at Austin, under contract to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the Minerals Management Service, US Department of Interior. The study was performed under Contract No. DACW 39-82-C-0014.

This report was prepared by Mr. Shin-Tower Wang and Dr. Lymon C. Reese, University of Texas at Austin, and reviewed by Mr. Gerald B. Mitchell, Chief, Engineering Group, Soil Mechanics Division (SMD), Geotechnical Laboratory (GL), WES. General supervision was provided by Mr. Clifford L. McAnear, Chief, SMD, and Dr. William F. Marcuson III, Chief, GL.

COL Dwayne G. Lee is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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CHAPTER 1. INTRODUCTION

Considerable evidence is available to show that reduced capacity under lateral load of piles supporting offshore structures can be due to the effects of piping and erosion by fluid.

The scour [1,2,3] around offshore structures on the sea floor caused by the erosive action of both oscillatory waves and unidirectional water currents has been studied for a long time. Soils around the foundations of these structures are scoured and carried away by currents thus reducing considerably the designed lateral capacity. Many factors controlling the scour phenomenon on the sea floor such as current velocity, wave characteristics, water depth, and shape of foundation have been examined in the past 10 years.

In addition to the scour of the sea floor around an offshore structure, the pumping force around the pile-soil interface caused by the cyclic movement of the pile presents another kind of scour phenomenon which has been less understood to date. A scour gap around the pile is formed after continual cyclic movement (shown in Fig. 1.1). The scour around a pile will reduce the lateral capacity of the pile, thus reducing the factor of safety. If the loss of resistance due to scour had not been considered in design, it is not beyond reason that the scour could cause a pile to fail leading to a failure of the structure.

The purpose of the study presented in this report was to develop a test that can be used to examine the scour potential of the soils around piles that support offshore structures. In order to provide a background for the experimental studies that were done, some description will be given

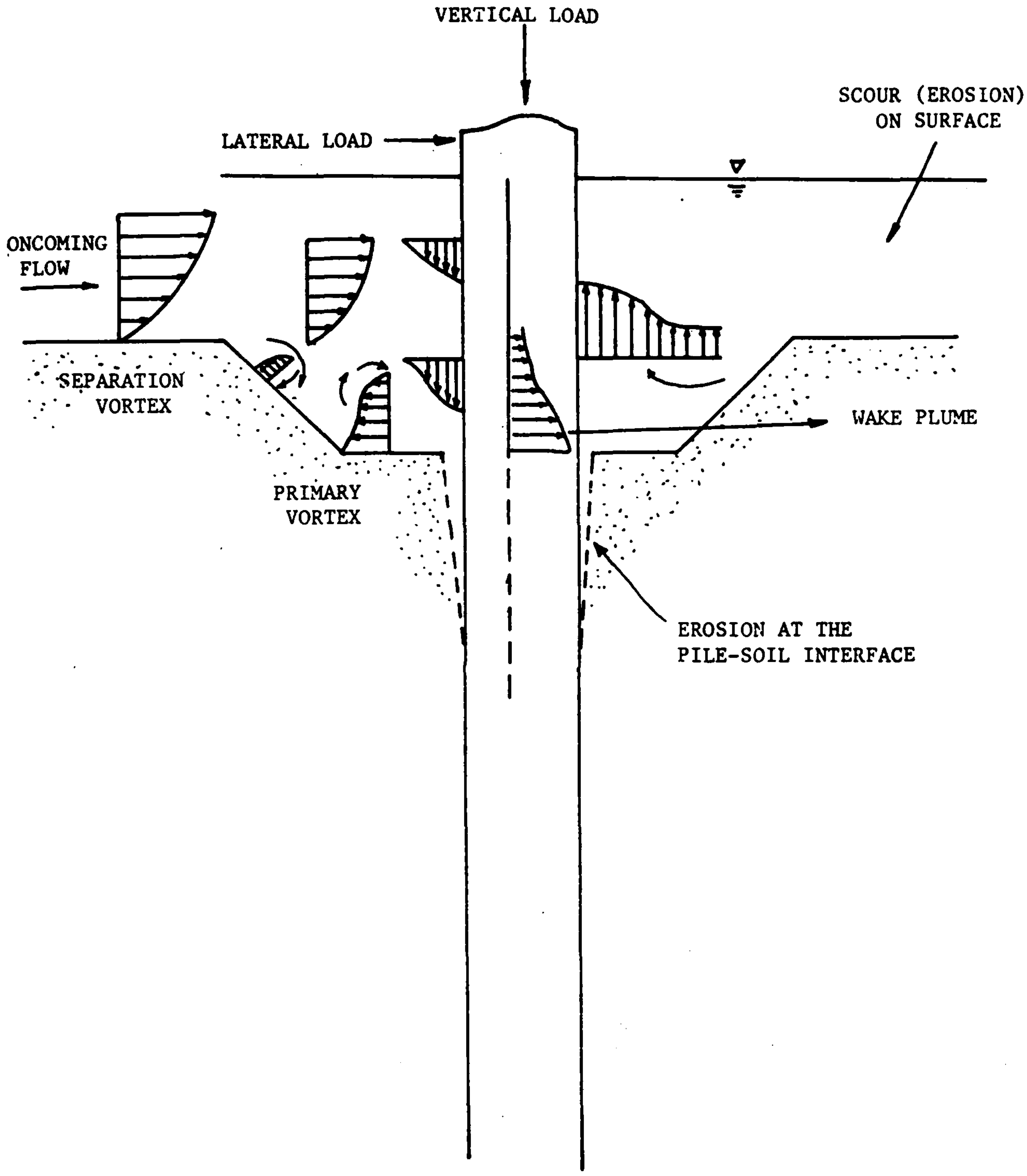


Fig. 1.1 Concepts related to scour around pile foundation

concerning the formation of scour holes around a pile foundation in the marine environment. Because the fluid flow is so complex at the pile-soil interface, this study is primarily directed toward an experimental rather than a theoretical approach.

The above discussion is general and is not specific with regard to soil type. Unidirectional water currents will scour non-cohesive, fine-grained sand to a considerable extent. There are cases where several feet of sand have been eroded around an offshore structure. Unidirectional currents will scour clays only to a limited extent, if at all. Erosion at the pile-soil interface is associated only with soils where a space will open or with cohesive soils. Cohesionless soils will collapse around the deflected pile or will move with the pile as it is deflected.

The results are aimed at providing an engineer in offshore design information such that the scour potential of the soil at a particular offshore site can be estimated.

This is the first of two reports that will deal with the loss of resistance of laterally loaded piles due to cyclic loading. In the second report, the loss of resistance due to two phenomena are studied. In addition to the loss of resistance due to scour, the loss of resistance due to cyclic deformations within the soil mass is examined. These two phenomena are used as a basis for explaining results of full-scale cyclic lateral-loading tests.

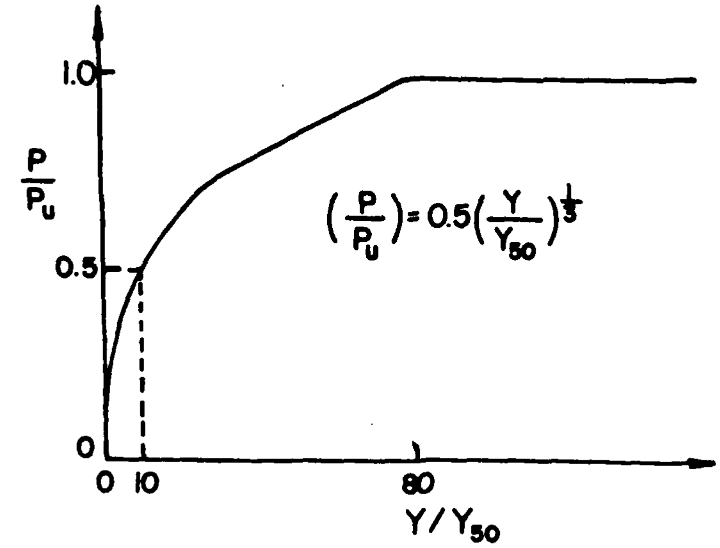
CHAPTER 2. THE INFLUENCE OF SCOUR ON PILE FOUNDATION DESIGN

The deflection of a pile under lateral load is dependent on the soil reaction against the pile. The response of the soil surrounding the laterally loaded pile can be described in terms of p-y curves[4] which relate the soil resistance to the pile deflection at various depths. Generally, these curves are nonlinear and depend on several parameters such as shear strength, pile geometry, and loading conditions.

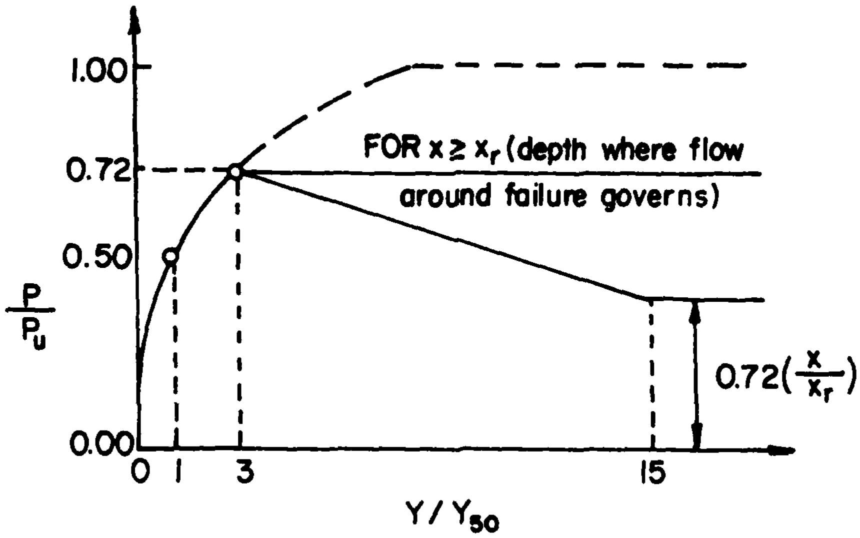
Because of the complex nature of the soil behavior around a laterally loaded pile, the major field experiments have led to the development of the current criteria for p-y curves. If the p-y curves for soft clay[5] and stiff clay[6] below the water surface shown in Figs. 2.1 and 2.2, respectively, are examined, it can be seen that there is a marked deterioration of soil response during cyclic loading. The decrease of soil response is caused by soil disturbance and the scour around the pile. As noted earlier, the scour occurs in cohesive soils and is thought to be one of the important factors influencing the loss of soil resistance.

As shown in Fig. 2.3a, the soil acts almost elastically to a given deflection and after that deflection a pile in clay will experience reduced resistance due both to scour and loss of resistance of the clay due to repeated loadings. Figure 2.3b shows that the loss of resistance due to scour is associated with the amount of soil that is removed around a pile as a result of the cyclic loading.

The current criteria for p-y curves for cyclic loading are based on limited data. These criteria may be conservative for some scour-resistant



(a) STATIC LOADING



(b) CYCLIC LOADING

Fig. 2.1 Characteristic shapes of the p-y curves for soft clay below the water surface (after Matlock, 1970)

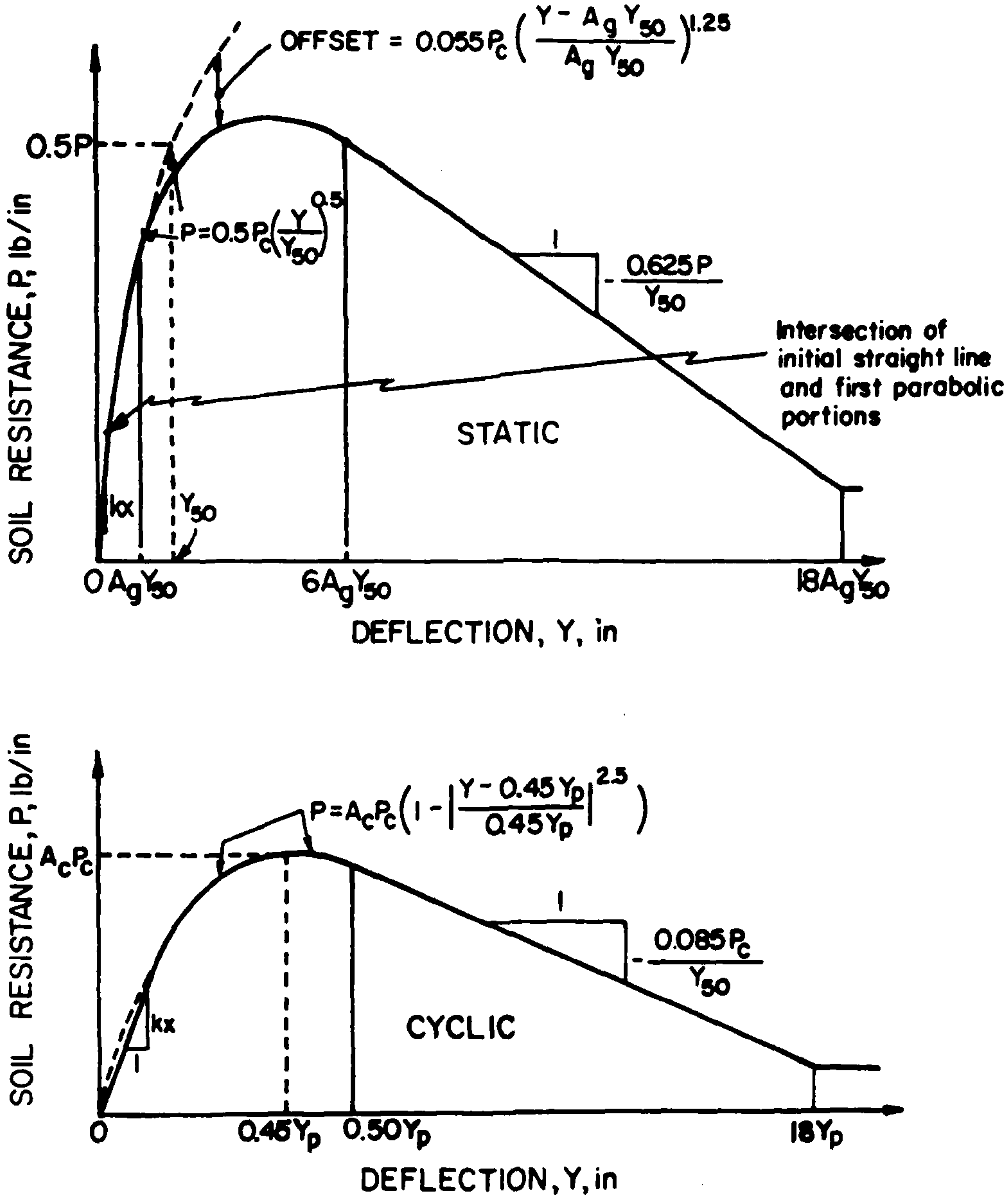


Fig. 2.2 Characteristic shapes of the p-y curves for stiff clay below the water surface (after Reese et al., 1975)

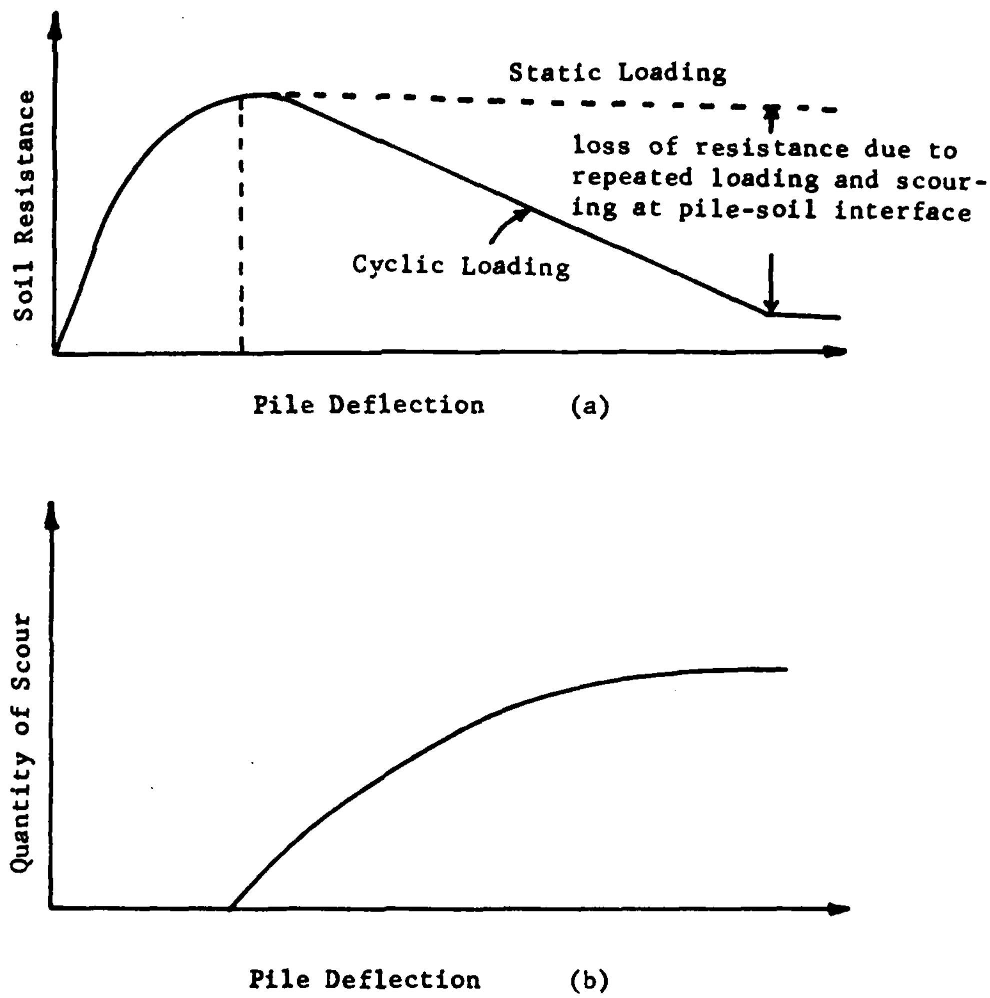


Fig. 2.3 Relationships of soil resistance, pile deflection and scour quantity

soil or may overestimate the soil resistance for some highly erosive soil. If a designer is to predict the correct soil response for cyclic loading, additional data on p-y curves are needed along with a sound understanding of the scour phenomenon in the field.

CHAPTER 3. THE MECHANISM OF SCOUR AROUND THE PILE-SOIL INTERFACE

Scour is the result of the interaction between a fluid-flow field, cyclic movement of the embedded pile, and the soil particles. The movement of the pile in response to an applied load is dependent on the soil reaction against the pile. The soil response is plastic beyond small pile movements, so if the deflection of the pile is larger than the elastic range of soil reaction, the plastic deformation of the cohesive soil cannot recover after the force is released and the water above the mudline will flow into the gap caused by the soil deformation. When an applied load such as wind or waves acts cyclically, the water in the interface will be pumped out on each cycle and both the pressure gradients and fluid velocities will be very high at that moment.

In the immediate vicinity of the pile the increase of the water velocity moving into the soil may be high enough to initiate movement of soil particles. After scouring, the soil particles will remain in the gap or, if the pumping force is continual and large enough, the soil particles will be washed out of the interface. Thus, the gap will be enlarged by the scour with a resulting reduction of soil resistance.

The significant scour mechanism in the interface mentioned above probably depends on many factors, such as mean diameter of particle, permeability, density of soil, shear strength, speed of cyclic force, elapsed time, and pile diameter. The experimental work was primarily concerned with the effects of altering some of these variables.

CHAPTER 4. THE RESEARCH APPARATUS AND PROCEDURES

The scour due to the pumping of the fluid in the pile-soil interface is one of the most complex of fluid-flow problems. A study was undertaken to find the best way to simulate the scour at the interface. Several ideas were considered and it was decided to construct a laboratory apparatus that would simulate the scour mechanism on a small scale. The apparatus is described in this section. It seems reasonable that the scour at the interface if the pile is in clay will depend not only on the flow characteristics of the fluid causing scour but also on the resistance of the clay. According to the studies by Sherard[7], the more dispersive the clay the more easily it will be eroded by water flow. Because the pinhole test is a standard test to study the dispersive properties of clay, there is a possibility that the pinhole test can also be used to evaluate the scour potential around a pile. The use of the pinhole test will be described later.

4.1 PILE-SOIL SCOUR POTENTIAL (PSSP) TEST

The laboratory test was conducted, as shown in Fig. 4.1, in a container (1 ft wide, 3 ft long, and 1 ft deep) made from sheet plastic. An electric motor with variable speed applied the cyclic movement on the rod by a connection bar. The 3/4 in. diameter rod was drilled into a soil sample (6 in. diameter and 7 in. long) and the end of the rod was connected with the bottom plate of the sample mold by a hinge to simulate the upper portion of the pile movement in the field. Water was maintained 2 in. above the surface of the sample. The displacement of the rod was varied by changing the eccentricity of a connection bar on the driving disk which

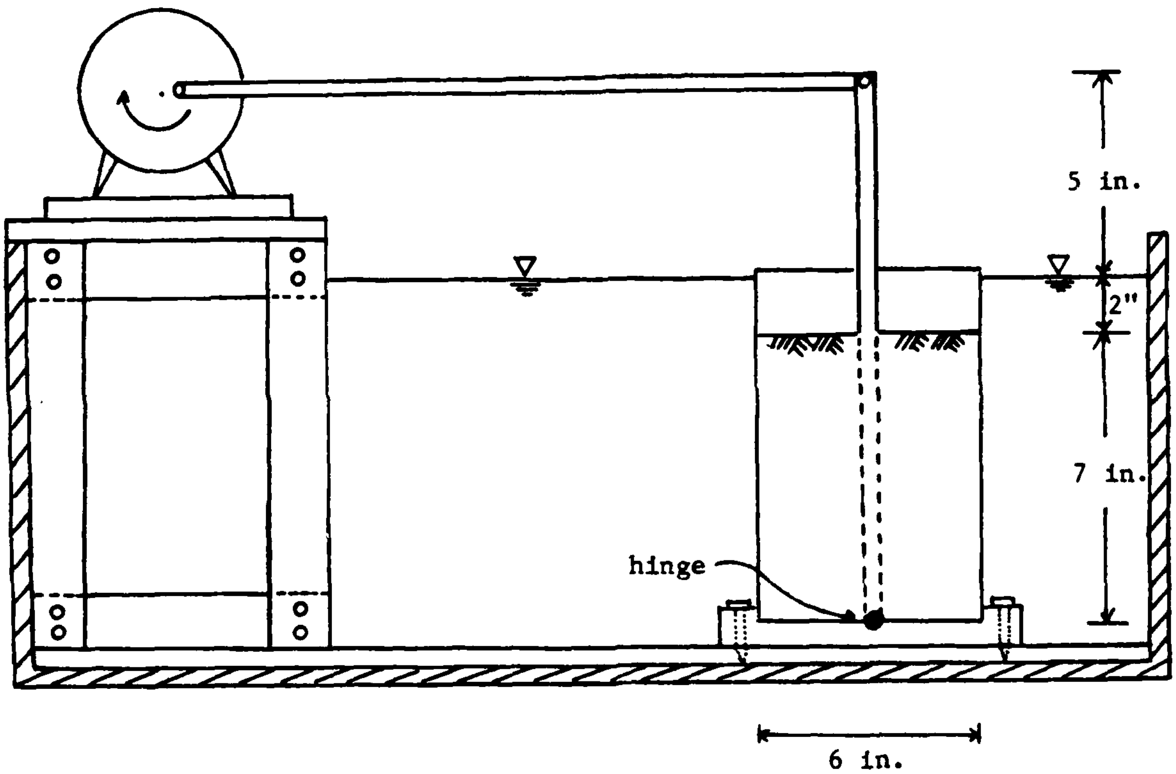


Fig. 4.1 Apparatus used in pile-soil scour potential test (PSSP Test)

was mounted on the variable-speed electric motor. The details of some of the components of the test are shown in Fig. 4.2. The test procedure and measurements are as follows:

A. Sample Preparation

1. Disturbed samples: a representative amount of air-dry, disturbed soil was pulverized using a mortar and a rubber-tipped pestle, sieved through a No. 40 sieve, and compacted to the specific density by the AASHO compaction method.[8] The disturbed sample with a 6-in. diameter and a 7-in. height was compacted in 5 layers with a 10-lb hammer using 56 blows per layer. A water content higher than the optimum moisture content was used in compaction in order to get a high degree of saturation. After measuring the weight and water content of the sample, a high back pressure was applied to the sample until the sample was fully saturated. Then the rod was drilled through the sample and the sample placed into the testing apparatus.
2. Undisturbed samples: undisturbed samples from the field were trimmed into the CBR compaction mold for testing. If 3-in.-diameter samples were taken from the field, the compaction sample was prepared with the same density as the undisturbed sample and a hole drilled at the center of the specimen to fit the 3-in.-diameter undisturbed sample to be inserted. The combined soil sample (6-in. diameter) with a 3-in.-diameter undisturbed core was used for the test.

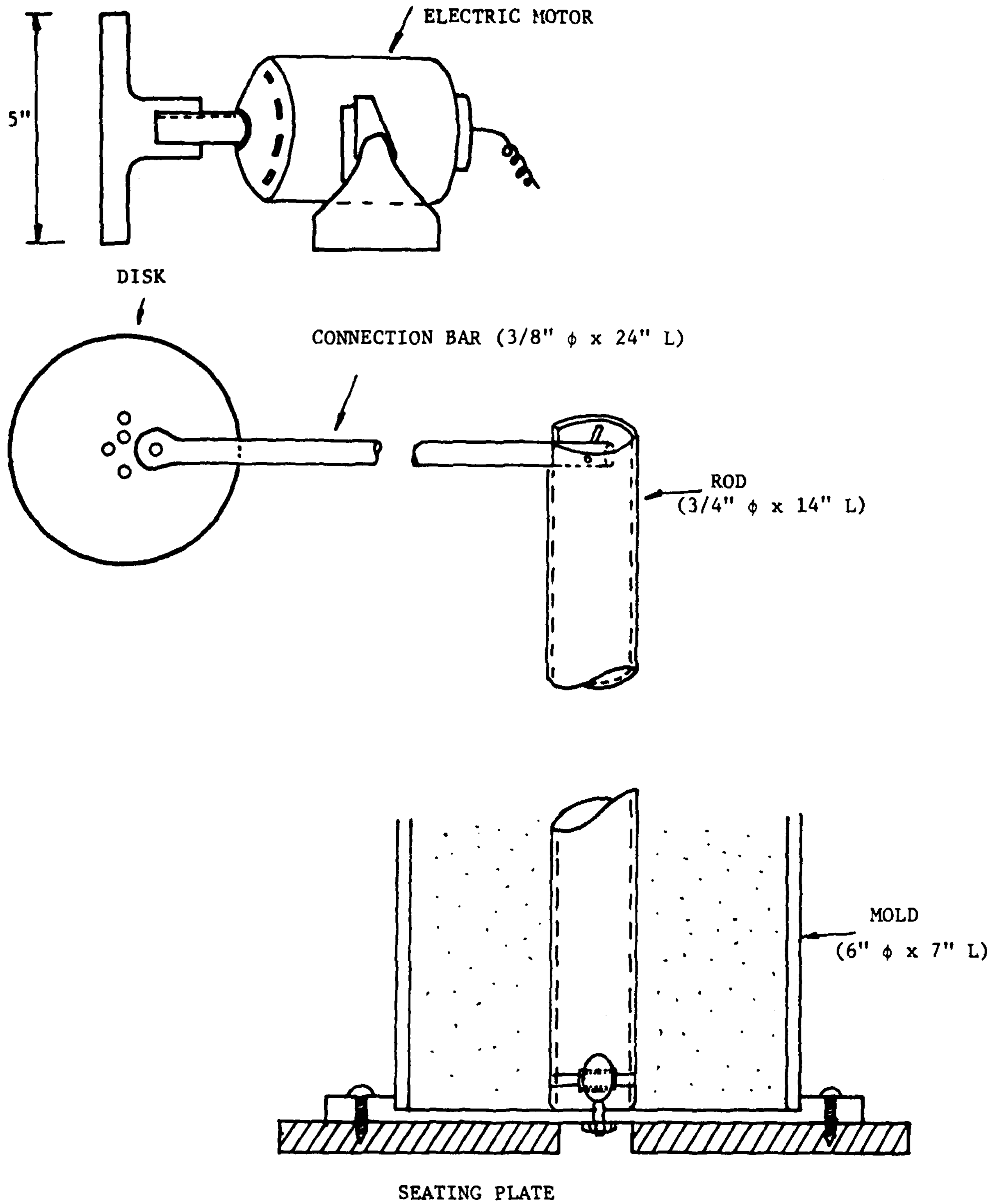


Fig. 4.2 Details of components of PSSP test

The weight of the combined sample was obtained, the rod was drilled through the undisturbed core, and the sample and rod were placed into the apparatus for testing.

B. Test Process

1. A thin disk with a central hole was placed around the rod. The hole was sized to match the maximum deflection of the rod at the surface of the soil sample.
2. The eccentric distance was adjusted on the disk of the electric motor so that the first applied pile deflection was 0.8 mm.
3. A constant speed of cyclic movement was used, and the frequency of load application was set at 60 RPM. The test was run for one hour.
4. A wash bottle was used to suck the suspension into a one-liter glass beaker. The soil left on the thin disk was carefully removed by washing and transferred to the same glass beaker. The weight of the soil was obtained after oven drying.
5. Steps 2 through 4 were repeated by increasing the deflection in 0.8 mm increments for each test run.
6. The test was discontinued when the applied deflection reached one-tenth of the diameter of the rod.

C. Data from Test

1. The amount of scoured soil was measured after oven drying and the weight was accumulated for each incremental deflection. A plot was made of the weight of scoured soil vs time.
2. Grain-size curves have been widely used in the identification and classification of soils. Because the size of the individual particles of a soil is an important parameter in scouring, the grain-size curve of the scoured soil was compared with that of the original soil samples to see if some of the particles were not scoured. The grain-size analyses were performed according to ASTM[9] standard procedures.

4.2 PINHOLE TEST

The pinhole test developed by J. L. Sherard[7] measures directly the dispersibility of compacted fine soils when water is caused to flow through a small hole punched in a specimen.

A specimen 1.5-in. long and 1.5-in. in diameter was compacted in a cylindrical mold of Sherard's design. For convenience in using a 3-inch undisturbed sample without trimming, both 1.5-in and 3.0-in.-diameter cylindrical molds were prepared.

The test specimen and apparatus from Sherard's work are shown in Figs. 4.3 and 4.4. The general test procedures are:

1. Soil samples must be preserved at the natural water content by shipping and storing samples in air-tight bags or containers.

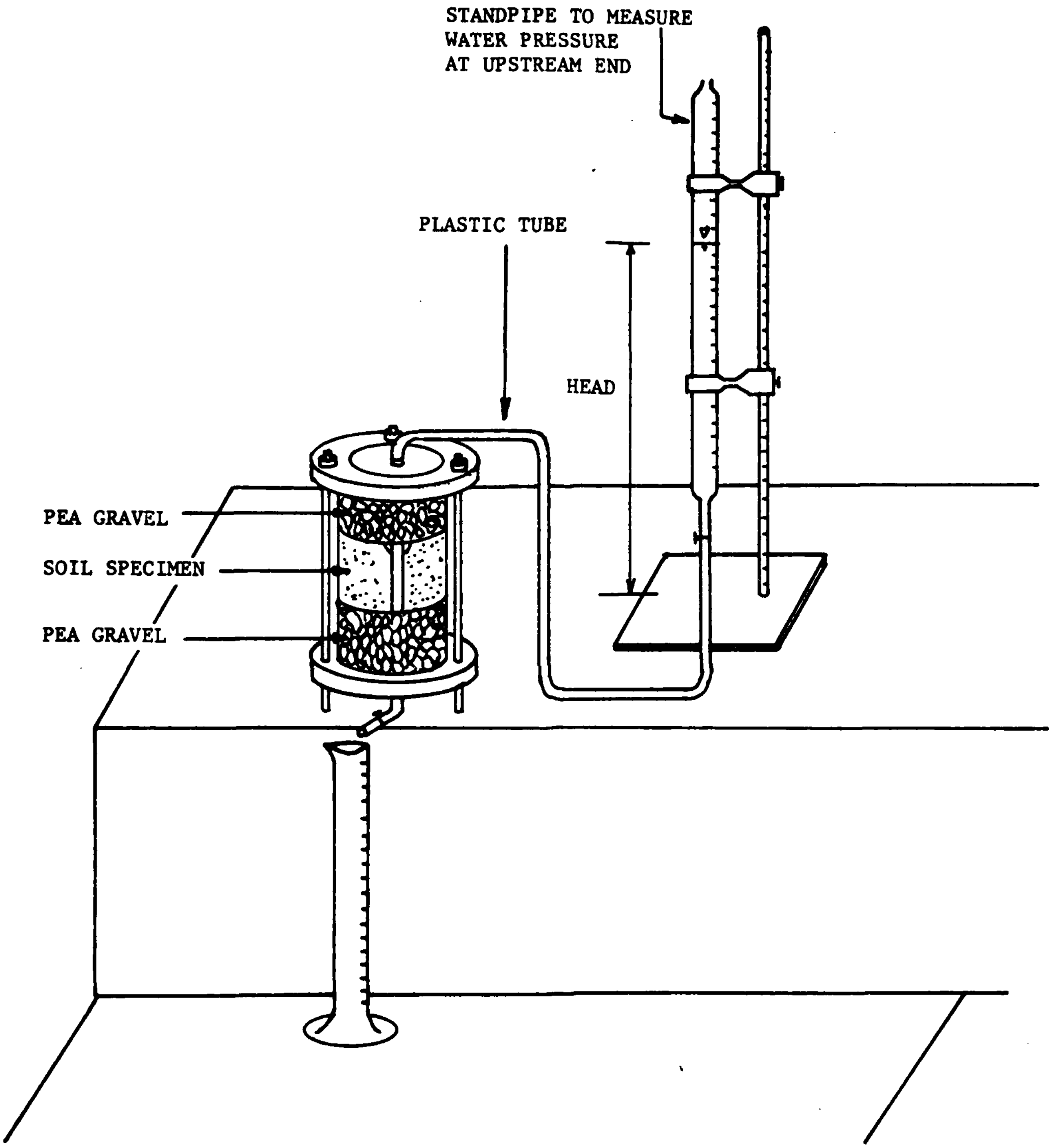


Figure 4.3 Apparatus for pinhole test

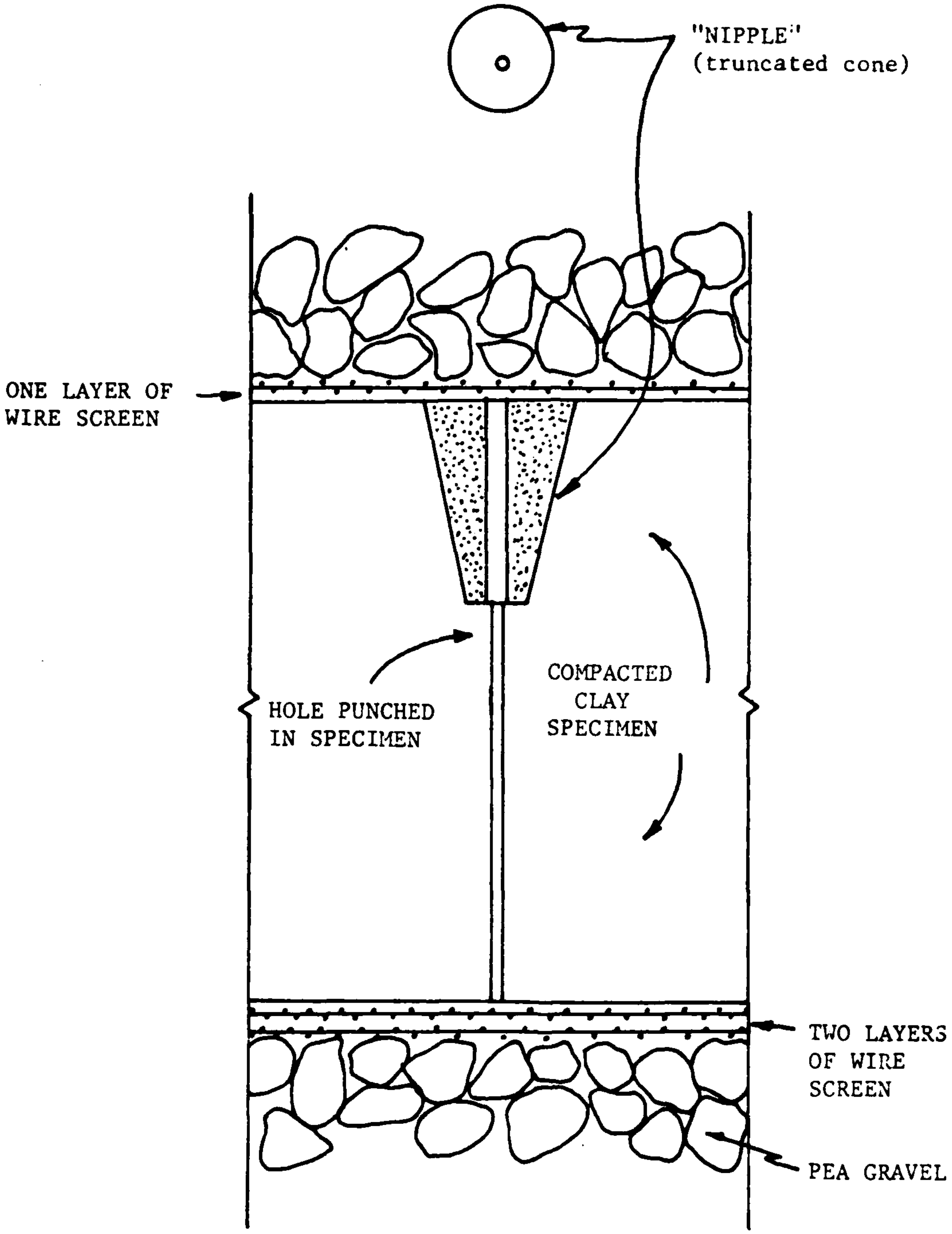


Fig. 4.4 Section through pinhole test specimen

2. If the material contains particles of coarse sand or gravel, these are removed by passing the material through a No. 10 sieve (2 mm).
3. The natural water content is measured and the water content is brought to near the plastic limit by adding the required water (or by gradually drying, if too wet). All water added should be distilled water.
4. The 1.5-in.-long disturbed specimen is compacted in the 1.5-in. cylinder on top of pea gravel and wire screen in five layers with 16 tamps per layer using a 2-lb hammer. For the testing of undisturbed soil, the 3-in.-diameter and 1.5-in.-long sample is extruded from the Shelby tube and trimmed into the cylindrical mold. The gap between the wall of the cylinder and the specimen is sealed with wax, then the wire screen and pea gravel is placed on the top and the bottom of the specimen.
5. A plastic nipple is pushed into the top of the specimen with finger pressure and a hole is punched through the nipple with a 1.0-mm-diameter stiff steel wire (hypodermic needle).
6. After the apparatus is assembled, water is percolated through the hole in the sample. The heads of water used are 2 in., 7 in., 15 in., and 40 in. (50 mm, 180 mm, 380 mm, and 1,020 mm) for time periods of 5 to 10 min at each head. The quantity of flow is measured continuously with a stop watch and cylindrical measuring flasks (10 ml, 25 ml, and 50 ml). The color of water is observed by looking both through the side of the flask and vertically through the column of fluid in the flask.

7. At the end of the successive flow tests, the apparatus is dismantled and the soil specimen is extruded from the cylinder and broken open to examine the size of the hole, which is measured approximately by comparison with the needle used for punching the hole.
8. The test is started with a head of 2 in. (50 mm). If no flow occurs, the test is stopped, the top of apparatus is dismantled, and a hole is repunched. Or the first hole is sealed and a new one is made. This occurs rarely.
9. The principal differentiation between dispersive and nondispersive soils is given by the test results under 2 in. (50 mm) of head. If the water that flows under 2 in. (50 mm) of head is visibly cloudy and does not become clearer with time, the specimen is failing in the fashion typical of dispersive clays. The main indicator of failure is the colloidal color of the water. Most dispersive clays erode rapidly under 2 in. (50 mm) of head with strong color in the water coming through the specimen. Usually for dispersive clays the flow continuously increases and reaches a maximum value limited by the hydraulic capacity of the equipment in 2 to 5 min of flow (about 1.5 to 2.0 ml/s). The test is continued for 10 min. Unless the color of the flow clears substantially, the test is then completed. For the typical dispersive clay the hole will normally be increased to about three needle diameters after 10 min of flow. The soil is classified as highly dispersive (D1).

10. If the water at 2 in. (50 mm) of head has a slight but easily visible color as seen from the side of the flask at the end of 5 min, the test is continued for 10 min. If water continues to be colored, the test is stopped. If the rate of flow at the end of 10 min has not exceeded 0.8 ml/s, and the hole diameter does not exceed 1.5 needle diameters, the soil is classified as dispersive (D2). If the test is stopped at the end of 10 min and the results classified as ND4 and D2, the test should be repeated with a new specimen to see what happens by raising the head to 7 in. (180 mm).

11. If the flow under 2 in. (50 mm) of head is clear (or has only a very slight trace of color as seen from the side of the flask) at the end of 5 min, the head is raised to 7 in. (180 mm) and the test is continued (rate of flow is usually 0.3 to 0.6 ml/s).

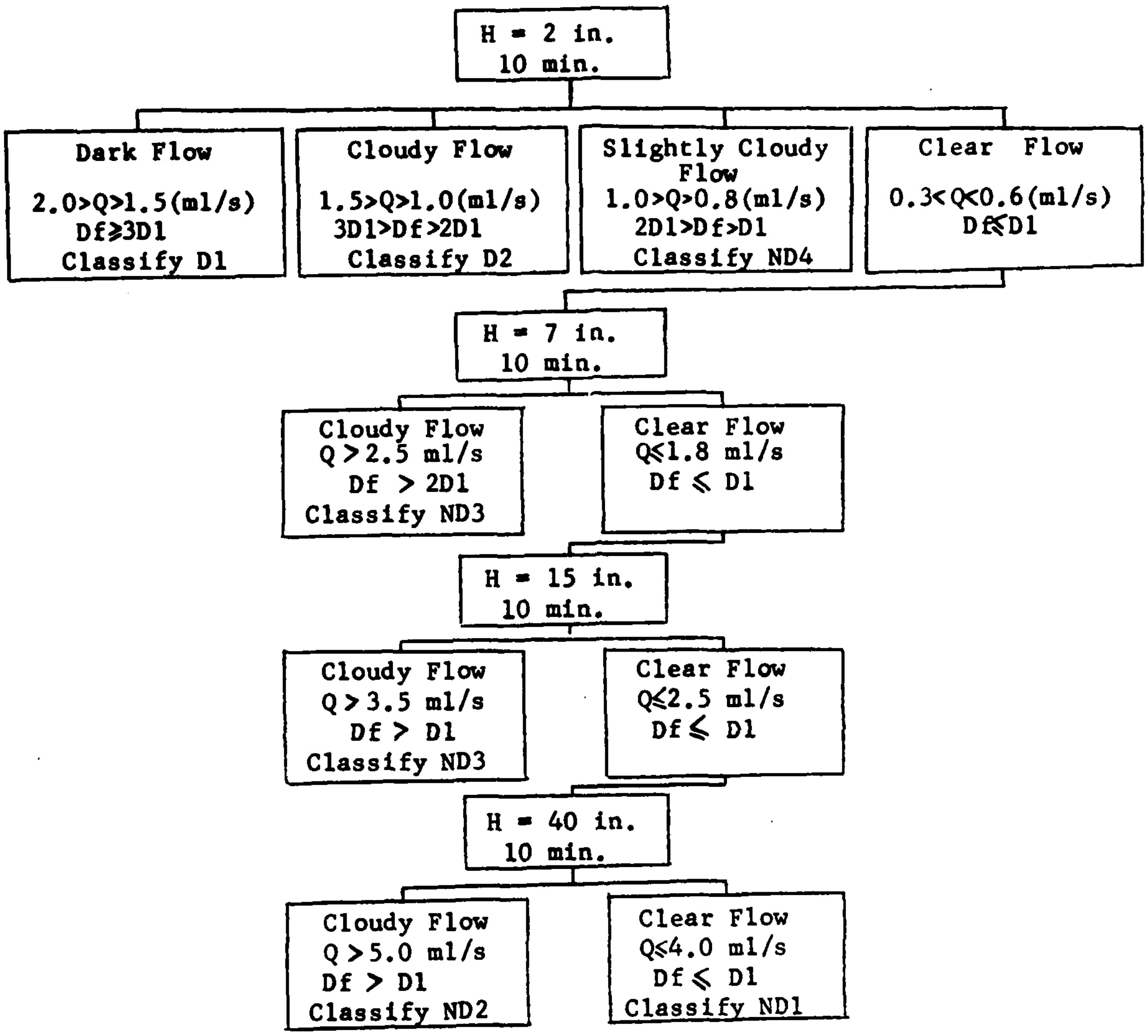
12. If the water continues to flow clear at 7-in. (180 mm) of head, or if it has only a trace of color as seen from the side of the flask, after 5 min the head is raised to 15 in. (380 mm) and the test is continued (rate of flow is usually less than 1.8 ml/s).

13. If the water has color and rate of flow increases rapidly, the test is stopped. The soil is classified as intermediate (ND3). The flow at the end of the test will generally exceed 2.5 ml/s, and the hole size will be larger than 2 needle diameters.

14. If the flow is completely clear as seen from the top of the measuring flask, the head is raised to 40 in. (1,020 mm) after 5 min (rate of flow is usually less than 2.5 ml/s).

15. If the flow has a slight color or exceeds 3.5 ml/s, the test is stopped and the soil is classified as nondispersive (ND3).
16. If the flow continues completely clear at a rate usually less than 4.0 ml/s, the soil is classified as nondispersive (ND1). There should be no noticeable erosion of the hole in the sample at the end of the test.
17. If the flow has a bare trace of color or exceeds 5.0 ml/s, the soil is classified as nondispersive (ND2).

The criteria of steps 9 through 17 are summarized in Fig. 4.5.



Note: Initial pinhole diameter = D1 = 1.00 mm

Final pinhole diameter = Df

Quantities of flow = Q

Fig. 4.5 Sequence of testing and classification of test results for pinhole test

CHAPTER 5. RESULTS AND ANALYSES

5.1 MEASUREMENT OF RESISTANCE OF SOIL TO INTERFACE SCOUR

Various soil properties such as grain-size distribution, percent and type of clay, and cohesive shear strength of clay may be selected for study in regard to scour resistance as measured by the PSSP test. In the experiments aimed at the development of the method of analysis, four typical soils whose properties are summarized in Table 5.1 were selected for measurement of scour resistance. All these samples were prepared by the AASHO compaction method and the soil density kept as close as possible between specimens. The speed of the electric motor was maintained at 60 RPM.

The test results are shown in Fig. 5.1. Because the rod deflection was changed every one hour in the PSSP test, the dry weight of scoured soil was measured and accumulated every period. The comparison of the relative scour resistance was based on the total quantity of scoured soil after testing. The more the scoured soil, the higher the scour potential will be. If the total quantity of the scoured soil is less than 5 gm the soil is defined as scour resistant. Using this criterion, samples SN2, SN3, and SN4 are all scour susceptible soils. The soils with the weight loss more than 20 gm such as the samples SN3 and SN4 seem to have higher scour potential.

It is apparent that the sample SN1 (fine sand) has significantly more scour resistance than the others. Confirming the scour resistance of sand, no scour was observed around the piles during the cyclic, lateral-loading test performed at Skyway Bridge, Florida.[10] Comparing the soil properties

TABLE 5.1 SUMMARY OF SOIL PROPERTIES

Sample	Soil Type	Specific Gravity (Gs)	Particle Size Distribution (%)			Atterberg Limits		
			Sand	Silt	Clay	LL	PL	PI
SN1	Fine Sand	2.65	96	4	0	--	--	--
SN2	Clayey Silt	2.70	3	72	25	29	16	13
SN3	Sandy Silt	2.68	23	59	18	31	20	11
SN4	Manor Clay	2.74	0	15	85	80	27	53

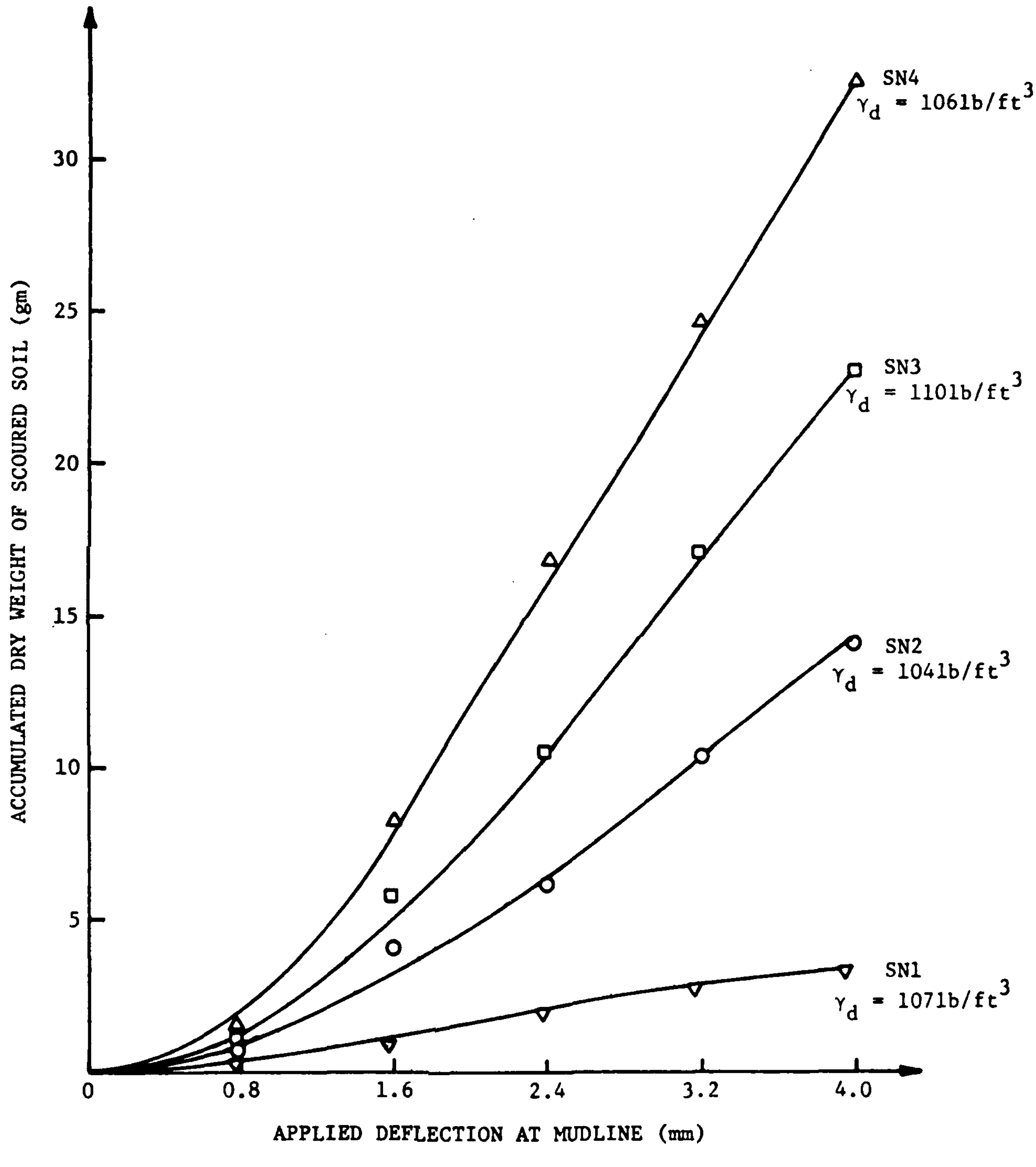


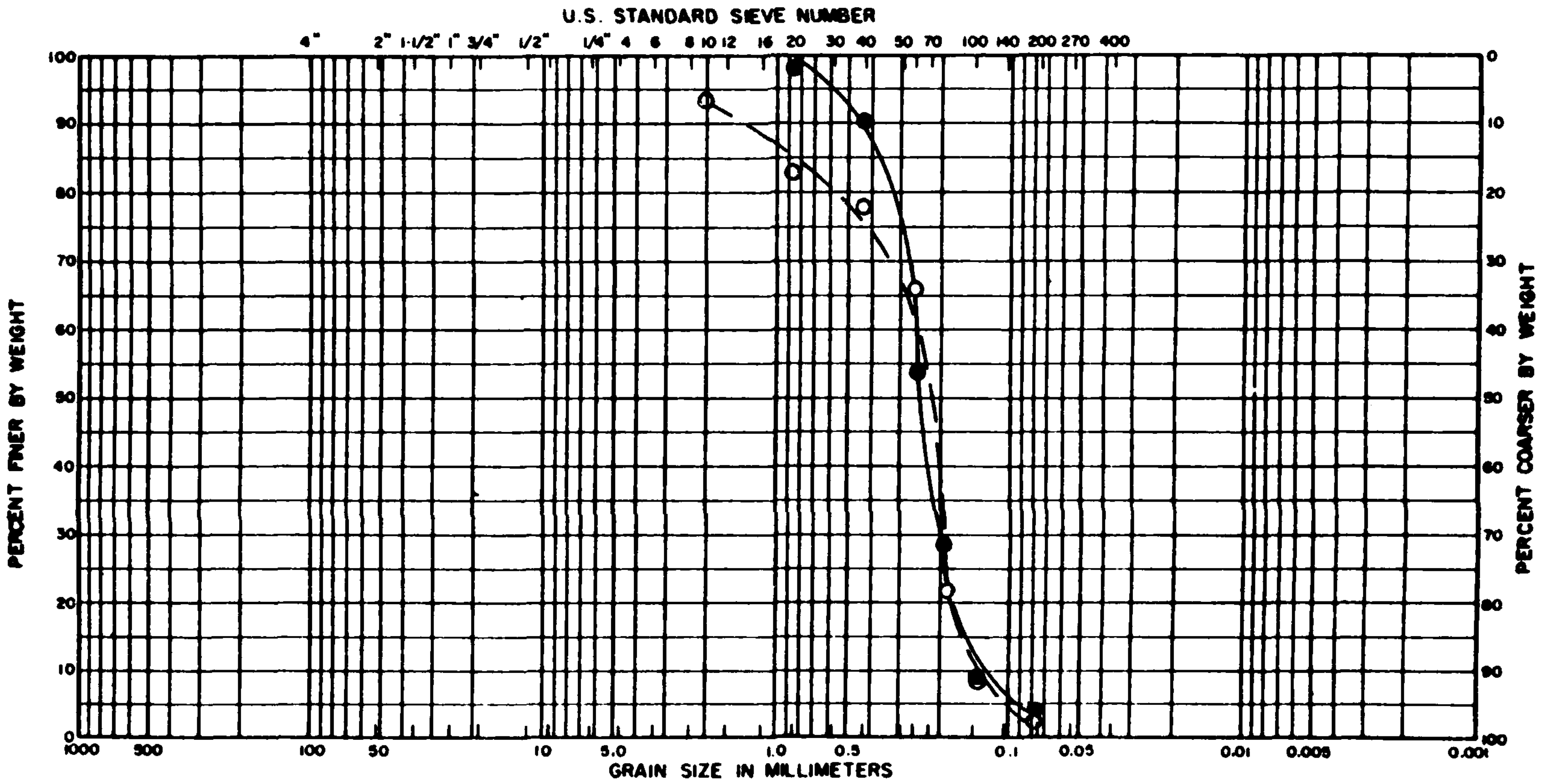
Fig. 5.1 Comparison of scour resistance of various samples

of sample SN1 and the sample taken from the field of Skyway Bridge, both of them were found to be cohesionless, medium to fine sand. Their curves of particle-size distribution are also very close (Fig. 5.2). Thus, it can be concluded that the nonplastic, medium to fine sand is a scour-resistant soil as indicated by both the PSSP test and field test.

The cohesive soil sample with the highest plasticity had a significant gap around the rod during the cyclic movement of the rod. The scour was clearly visible in photographs (Figs. 5.3 to 5.6). The enlarged gap from scouring of the cohesive sample SN3 is shown in Fig. 5.7, but no scour gap was found in the cohesionless sample SN1, shown in Fig. 5.8. Based on these results, the scour in cohesive soil needs to be carefully considered in pile design. In order to study the characteristics of soils that are scoured, the particle-size distribution of scoured soil and scour-resistant soil are all plotted in Fig. 5.9. Generally speaking, the particles are smaller for the scoured soil than for the soil in the specimens. This study seems to show that the particle size is an important factor regarding the scour resistance of soil.

5.2 MEASUREMENT OF THE INFLUENCE OF VARIOUS FACTORS ON SCOUR RESISTANCE

Because the scour at the interface of a pile and soil involves the interaction between fluid flow, cyclic movement of the pile, and soil properties, varying any one of these three factors will affect the scour process. The previous study shows that cohesionless sands are not susceptible to scour, therefore the further studies will be aimed only at clays.



○ Sample from Skyway Bridge

● Sample from SN-1

Fig. 5.2 Gradation curves of sample SN-1 and sample from Skyway Bridge

Fig. 5.3 View of Manor Clay during testing (Note: photograph taken after 10 cycles with a displacement of the rod of 0.8 mm)

Fig. 5.4 View of Manor Clay during testing (Note: photograph taken after 180 cycles with a displacement of the rod of 0.8 mm)

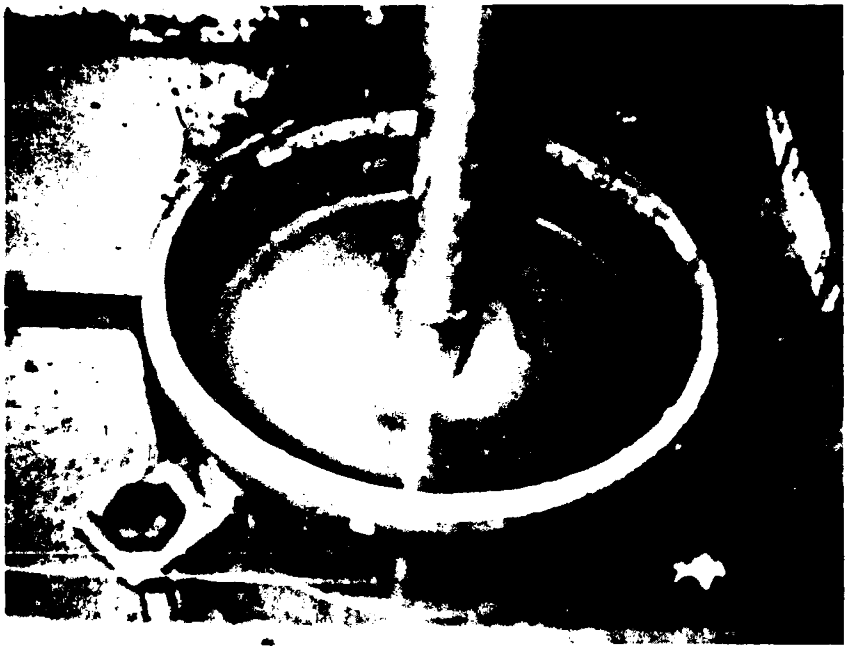


Fig. 5.5 View of Manor Clay during testing (Note: photograph taken after 300 cycles with a displacement of the rod of 0.8 mm)

Fig. 5.6 View of Manor Clay during testing (Note: photograph taken after 600 cycles with a displacement of the rod of 0.8 mm)

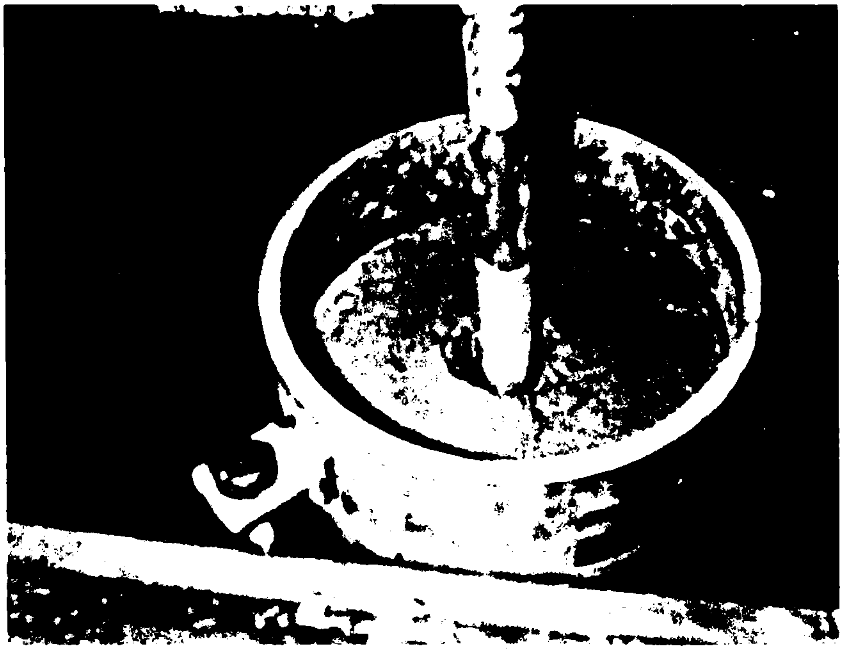
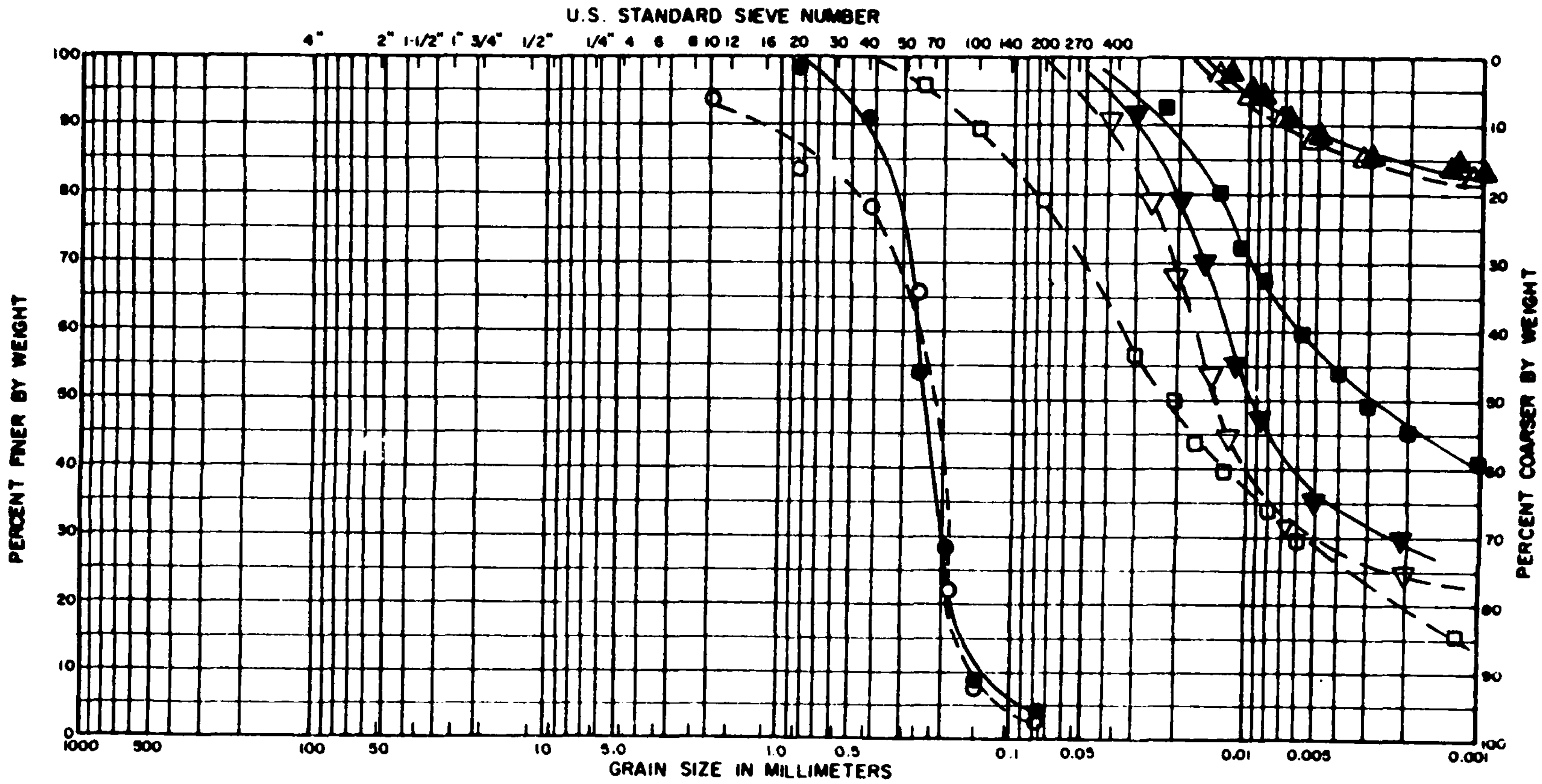


Fig. 5.7 View of scour gap after testing (Note: photograph taken from sample SN-3 after testing)

Fig. 5.8 View of non-scour gap after testing (Note: photograph taken from sample SN-1 after testing)



○ Sample from Skyway Bridge (no scour)
● Sample from SN-1 (no scour)
□ Sample from SN-3
■ Sample from the Scoured Soil of SN-3
▽ Sample from SN-2
▼ Sample from the Scoured Soil of SN-2
△ Sample from SN-4
▲ Sample from the Scoured Soil of SN-4

Fig. 5.9 Gradation curves of scoured soils and scour-resistant soils

The experimental program included changing some of these variables for detailed study as discussed in the following sections.

5.2.1 EFFECT OF SOIL PROPERTIES ON SCOUR RESISTANCE

A. Sample Disturbance

The cohesive shear strength generally is reduced by soil disturbance which is inevitable in pile driving. Because the Manor clay (sample SN4) with high sensitivity, fissures, and cementation is easily disturbed, the undisturbed Manor Clay taken from the field was used in this study (Fig. 5.10). The influence of soil disturbance on scour resistance is shown in Fig. 5.11. The scour resistance of the undisturbed sample is significantly higher than that of the compacted sample (fully disturbed). The decrease of the cohesive shear strength due to the destruction of cementation is a possible explanation for this effect.

B. Soil Density

Generally, as the density of a clay increases there is an increase in the shear strength and an increased scour resistance would be expected. Figure 5.12 shows the relation of soil density to the scour resistance of Manor clay. The scour does not change greatly with different densities and water contents for both sample SN2 and SN4. However, the lower percentage of clay in sample SN2 has some effect on scour resistance at the higher density.

Fig. 5.10 View of 6-in.-diameter undisturbed Manor Clay

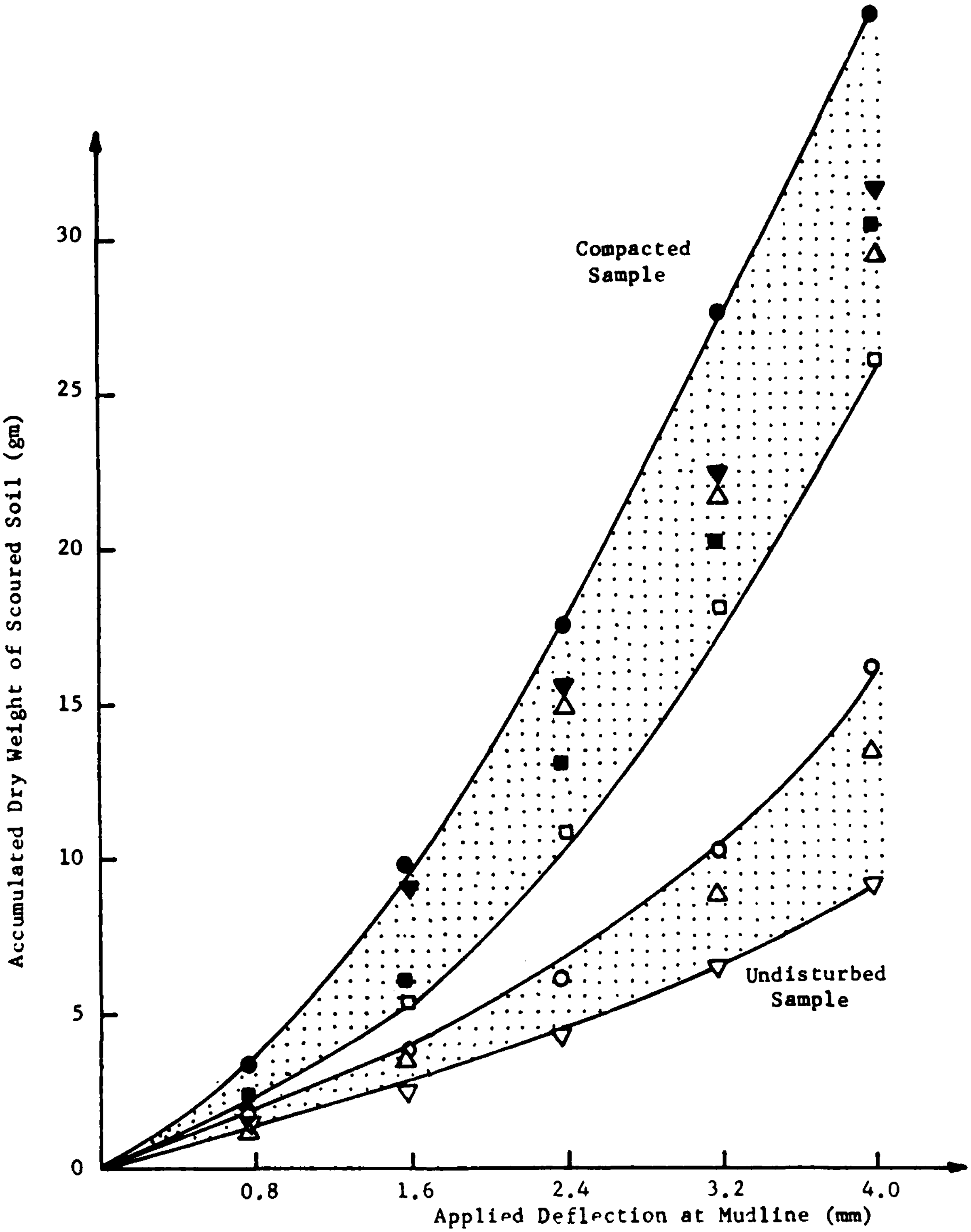


Fig. 5.11 Influence of sample disturbance on scour resistance of Manor Clay

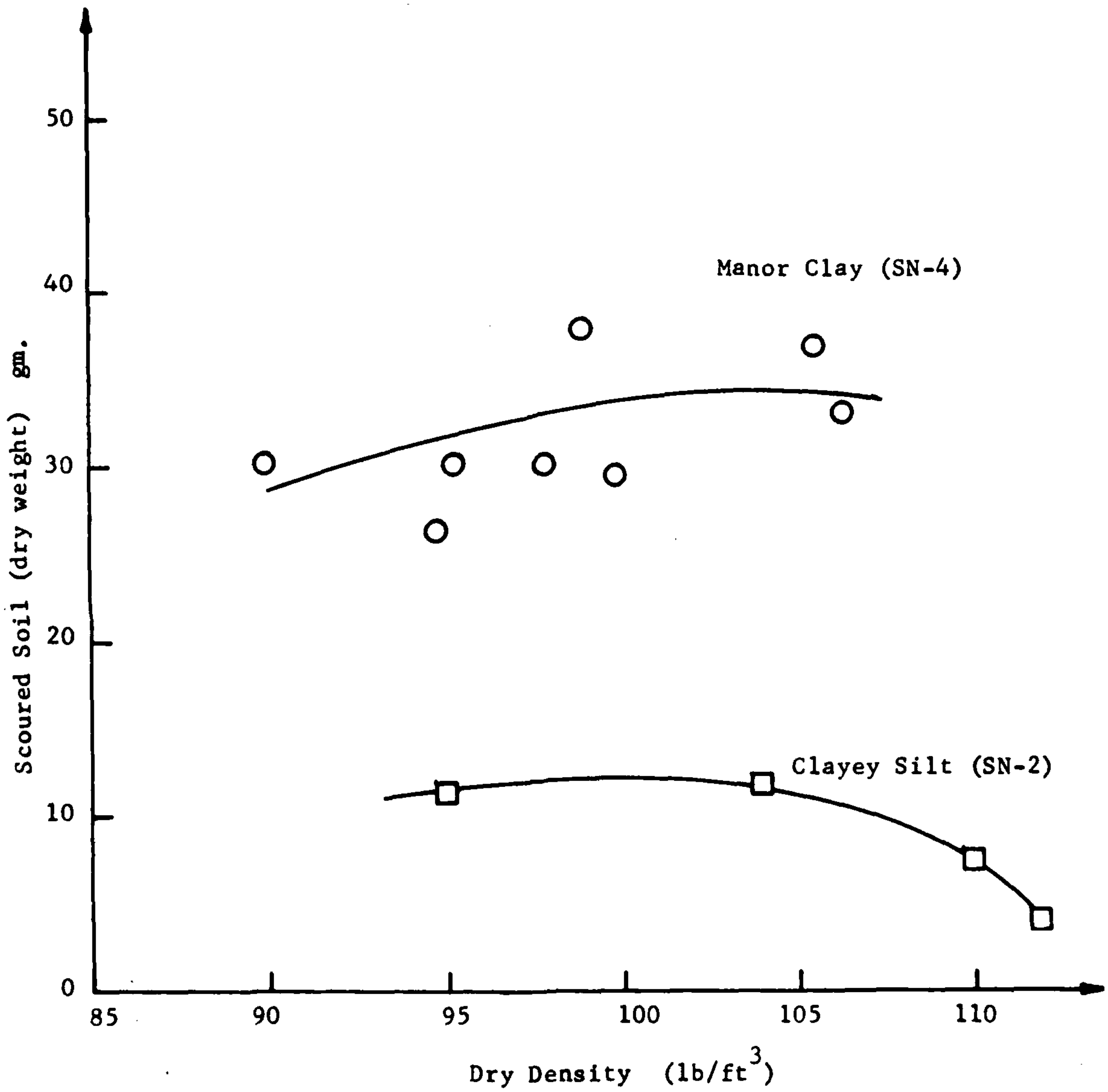


Fig. 5.12 Influence of soil density on scour resistance

5.2.2 FREQUENCY OF PILE MOVEMENT

Because the velocity of water being squeezed from the gap in the soil around a pile will undoubtedly influence the scour, the increase of the frequency of pile movement should have an influence on the rate of scour. On the other hand, the more the number of cycles, the more interactions between pile, soil and fluid there will be. It is believed that there is an increase in scour if the rod frequency is kept at 60 RPM and the number of cycles is increased. Figure 5.13 shows that the scour of Manor clay varies with the pile frequency. The more scour at higher speed of pile movement can be attributed to both the increase in cycles and in fluid velocities.

A. Number of Cycles

The scour is caused by cyclic movement of pile; thus, the number of cycles seems to be an important factor in scour process.

The dry weight of scoured soil is plotted versus the logarithm of number of cycles in Fig. 5.14. It may be seen that the scour is influenced both by the frequency and by the number of cycles. For a given deflection of the rod there must be number of cycles at which no more scour would occur but that equilibrium condition could occur at a very large number of cycles.

B. Fluid Velocity

The tractive force of fluid flow causes the soil particles to be loosened and eroded on the soil boundary. Because the magnitude of the tractive force is proportional to the fluid velocity, a knowledge of fluid velocity is necessary in making

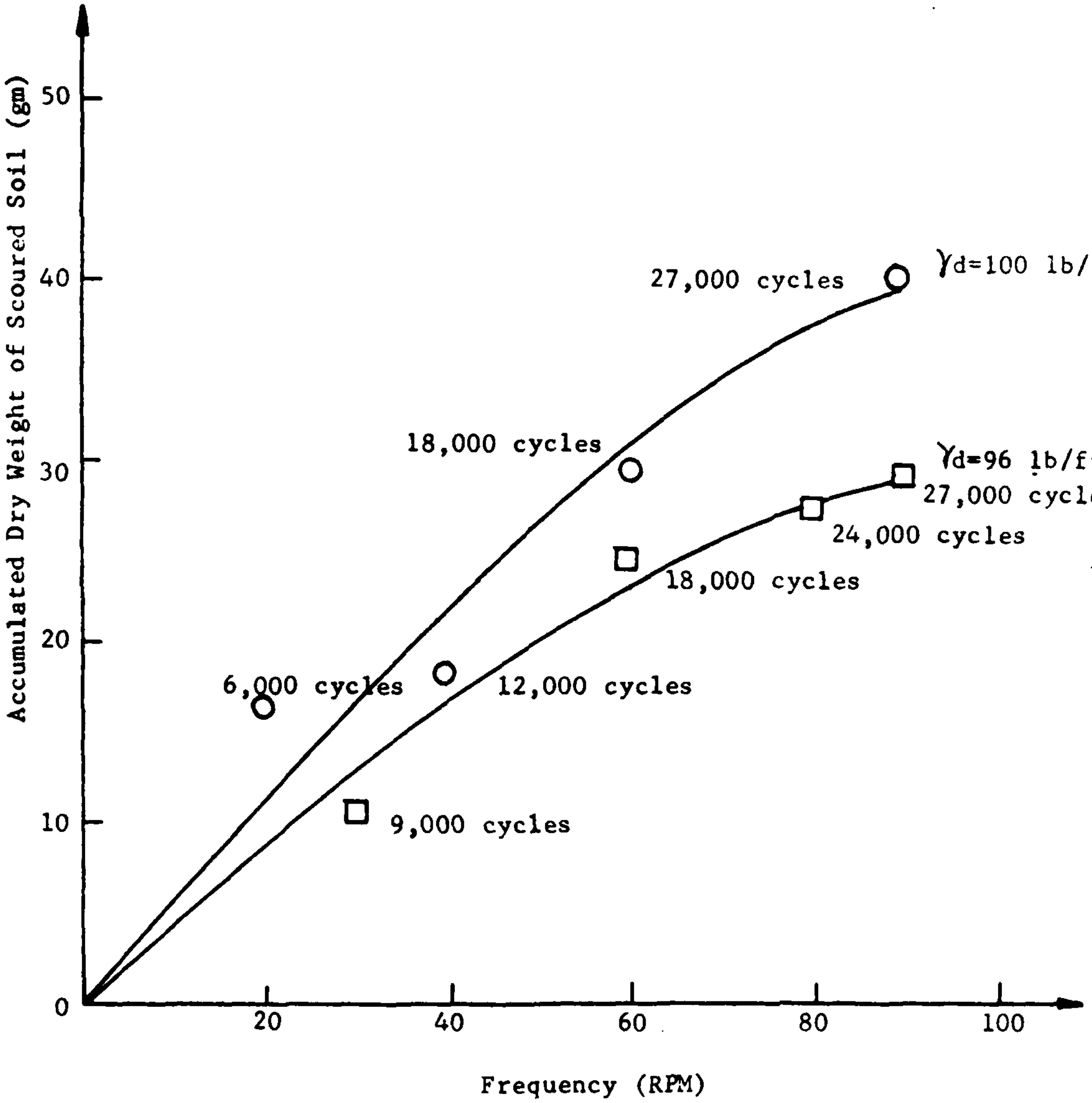


Fig. 5.13 Influence of pile frequency on scour resistance of Manor Clay

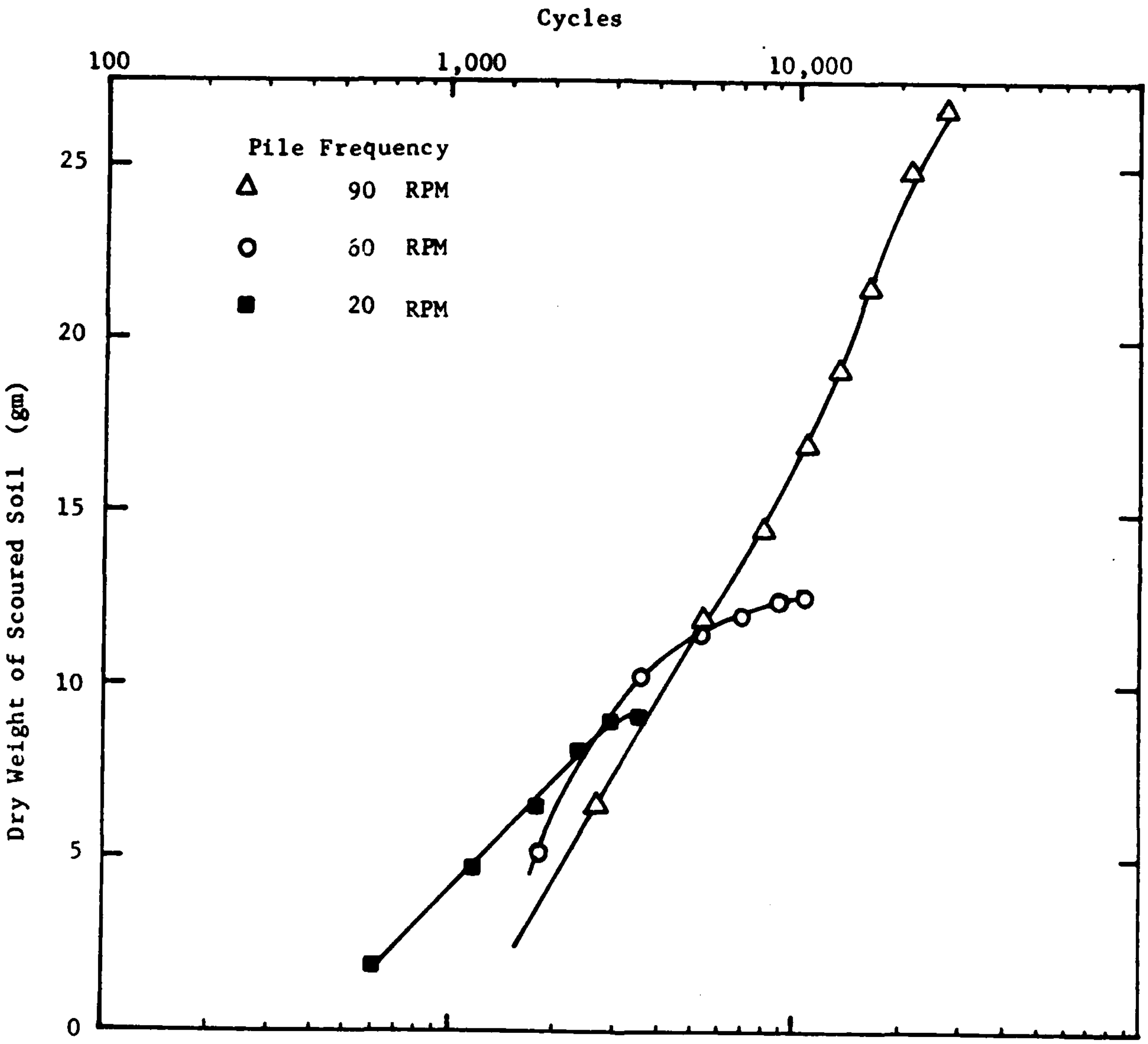


Fig. 5.14 Influence of the number of cycles on scour resistance of Manor Clay

analytical studies of the scour of soils.

As a means of developing an expression for the velocity of flow from the gap around a pile (or from the gap around the rod in the PSSP test), it is assumed that the pile or rod acts like a plunger in a cylinder. The further assumption is made that the average area of the gap is equal to one-half the area at the mudline. With these assumptions, the fluid velocity v in the PSSP test can be estimated simply as follows:

$$v = \frac{V \cdot \overline{f}}{A} = \frac{\frac{A}{2} \cdot L \cdot \overline{f}}{A} = \frac{L \cdot \overline{f}}{2} \quad \text{.........................(1)}$$

in which L = the length of the scour opening (length of rod);

V = the volume of scour opening;

A = the area of cross section of scour opening at mudline, and

$\overline{f}$ = the time required for the scour opening to be closed.

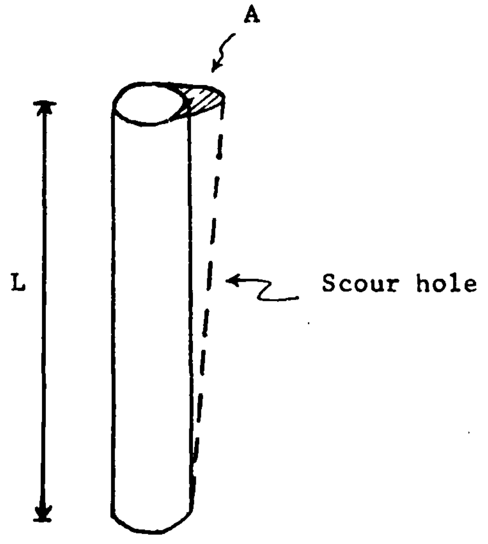


Figure 5.15 shows the influence of fluid velocities on scour at different numbers of cycles of loading for Manor Clay. The soil properties are probably influenced by the water at the pile-soil interface and vary with time in a complex manner. The swelling of cohesive soil generally causes a decrease of the interparticle bonding force and thus the critical shear stress required to promote scour is reduced. If the number of cycles is as low as 1800, the elapsed time is 1.5 hours at a frequency of 20 RPM, but only 20 minutes duration for 90 RPM. The variation of soil properties with time could be important and perhaps the dominant factor in scour; thus, the influence of fluid velocities may not easily be detected. The decrease of the interparticle bonding force due to a longer duration of testing is a possible reason to explain the more scour at a lower frequency in Fig. 5.15.

However, when the number of cycles is large and the duration of testing is long enough so that the soil properties at the interface are not likely to be changing much, the effect of fluid velocity is more apt to appear. Curves with the number of cycles over 7,200, where the duration of testing is longer than one hour, can be seen in Fig. 5.15. Samples acted upon by the higher fluid velocities seem to have a significant decrease in scour resistance at the same number of cycles. The influence of the variation of soil properties with time, mentioned before, seems not to be very

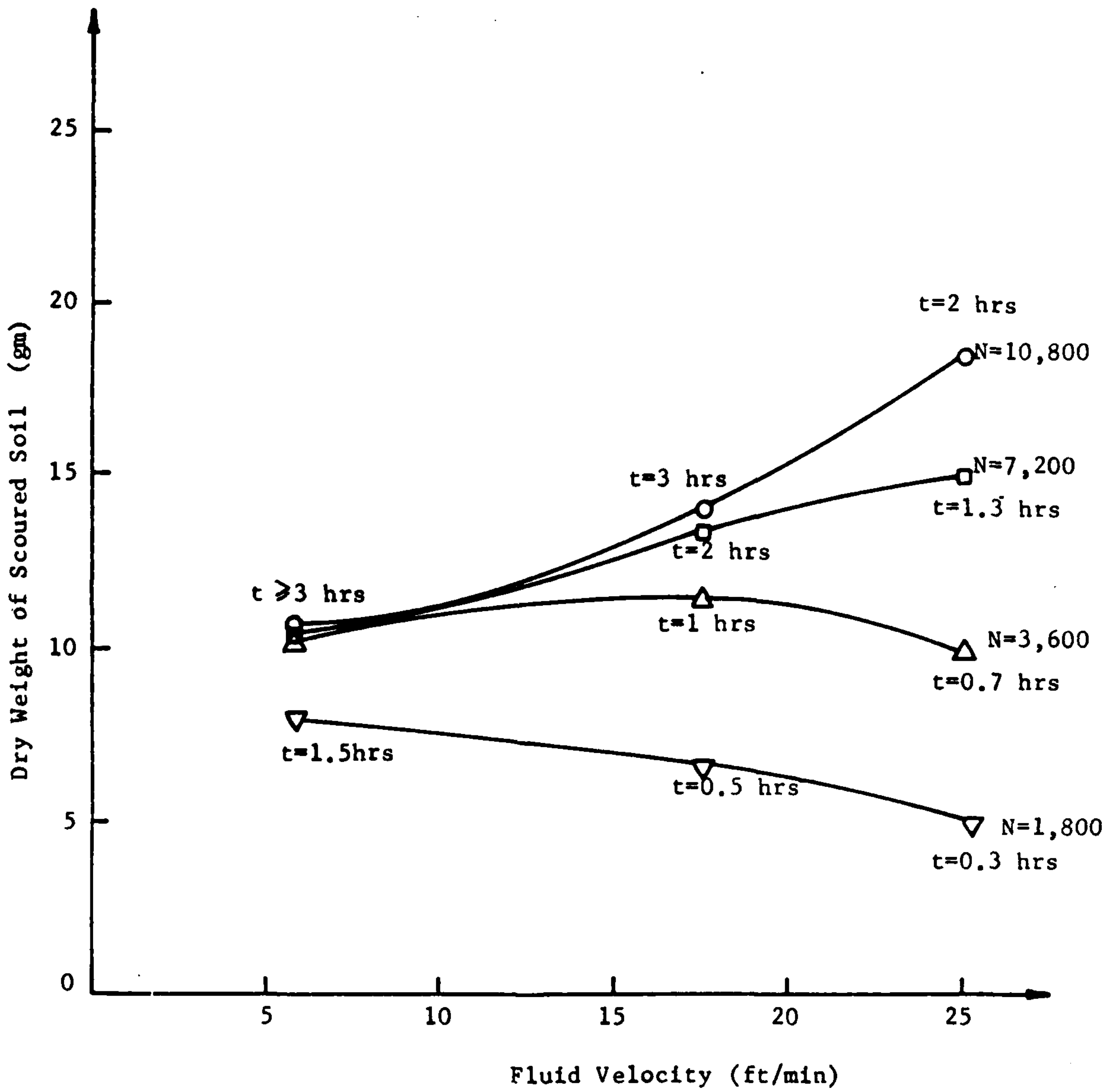


Fig. 5.15 Influence of fluid velocity on scour resistance of Manor Clay

significant and may be overshadowed by the increase of the fluid velocity.

Generally speaking, if the soil properties remain contant during a test, the high fluid velocity undoubtedly produces a greater scour than a low fluid velocity.

5.2.3 PILE DIMENSIONS

From Eq. 1, the fluid velocity is only a function of the depth of the scour hole and the pile frequency. However, the large diameter pile has more interface for scouring and probably the depth of the scour hole will indirectly be a function of the pile diameter. If so, the fluid velocity will be also affected by the pile diameter.

A comparison of the scour using different sizes of rods in the laboratory test is shown in Fig. 5.16. Because the PSSP test was not performed on a full-size pile and the length of the rod is constant, the rod diameter may not show any significant influence on the depth of scour. Without any change in scour depth, the interaction area of scour should be proportional to the rod diameter. Figure 5.16 shows that the relation between the curves is 3/4 to 1, which is precisely what it should be at the constant scour depth. The increase of the interface area for the large diameter rod could be the only reason to cause the more weight loss in PSSP test.

5.3 EQUILIBRIUM STAGE OF SCOUR AROUND THE PILE-SOIL INTERFACE

According to observations in the field, the scour process decreases with the increase of duration under the constant cyclic movement of piles.

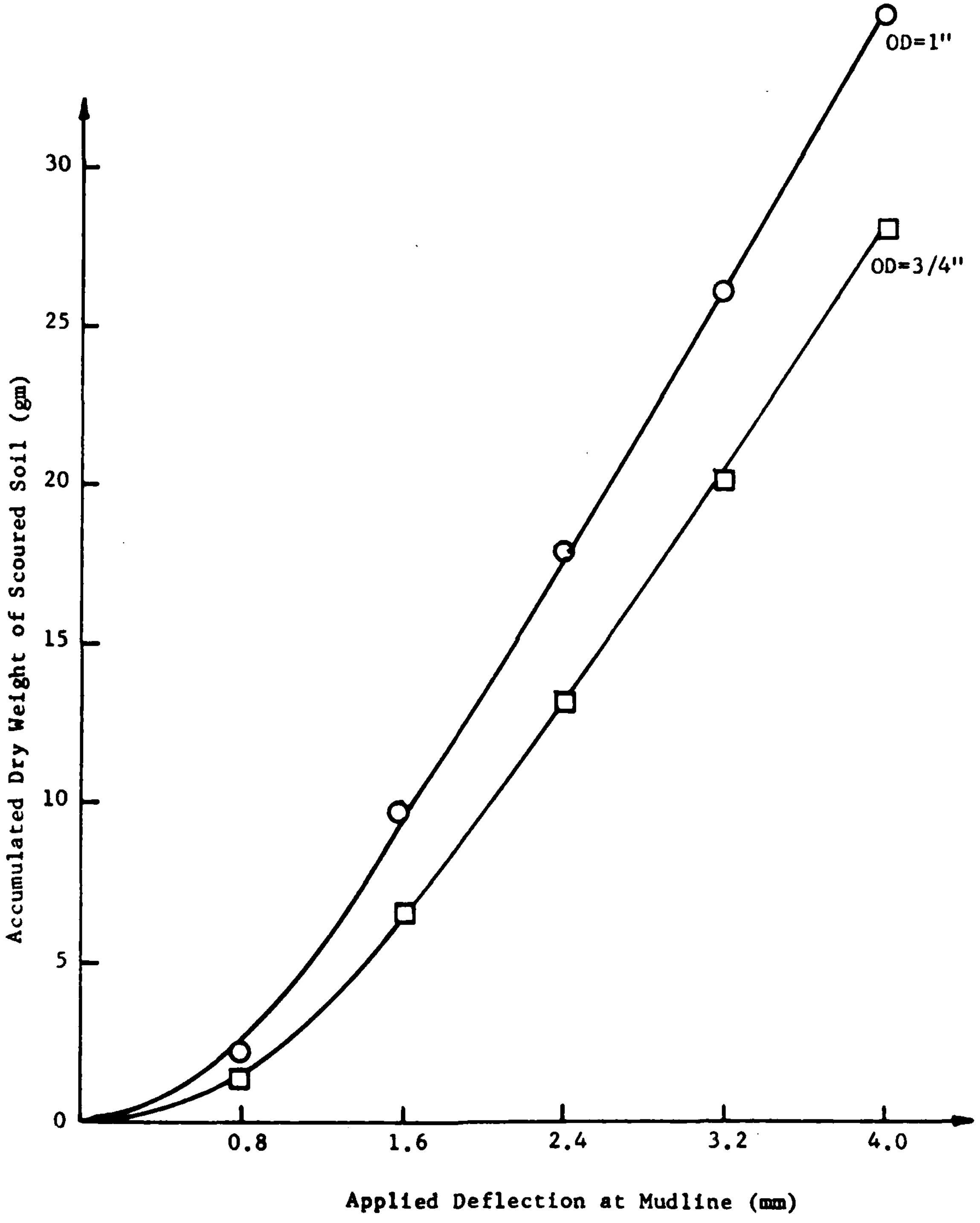


Fig. 5.16 Influence of pile diameter on scour resistance of Manor Clay

If the amplitude of pile movement is held constant by a layer of strong soil below the mudline, an equilibrium condition should develop at which little or no additional scour will occur.

Scour equilibrium is achieved when the volume of material removed by the water is decreased to a very small amount. At that moment, the scour opening is somewhat larger than would be indicated by the amplitude of cyclic pile movement.

The observations made during this study were that rapid and dramatic scouring normally took place during the first hour of each test, but the time to reach scour equilibrium appeared to be longer than one hour. It is apparent that the boundary conditions and many other factors affect the equilibrium stage. At present, there is no way to predict whether or not there is any similarity between the behavior of full-sized piles at offshore sites and the observations made in the laboratory. As noted earlier, the thrust of this study was to develop a simple laboratory test for ascertaining the scour potential of various soils.

The tests that involved the change of frequency with constant displacement show that the low speed of rod movement gave a slow scour process. According to the laboratory tests, the duration for the equilibrium stage at 20 RPM was about twice as long as that at 60 RPM (Fig. 5.17). Because the fluid velocity varied with the speed of pile movement, the quantity of scoured soil after reaching the equilibrium stage at 60 RPM is significantly higher than that at 20 RPM.

The equilibrium stage was not found in three hours of laboratory testing when the pile frequency was kept at 90 RPM as shown in Fig. 5.17.

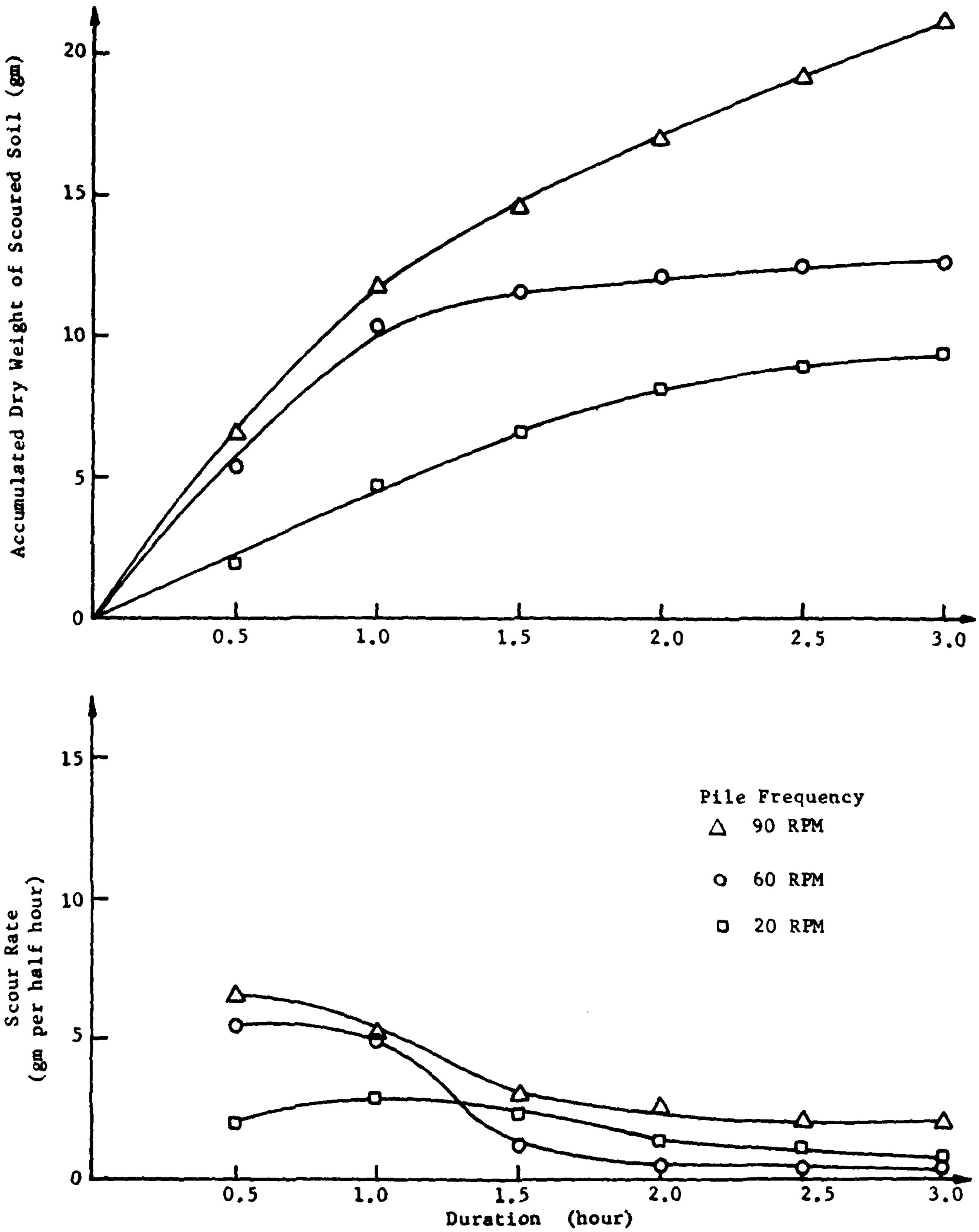


Fig. 5.17 Relationship between scour rate and duration of testing of Manor Clay

In order to gain further information the duration of testing was increased to 5 hours. However, the scour rate was still measurable at the end of testing as shown in Fig. 5.18.

Although the equilibrium stage sometimes cannot be observed properly in the laboratory due to the limit of testing time, the data do clearly show that the scour rate was gradually decreasing after one hour of testing. Based on these observations, the scour process can be divided into two stages in the PSSP test: stage one is called the main-scour stage and is where scour is occuring rapidly with a high scour rate, and stage two is called the residual-scour stage and is where the scour rate has become relatively constant. Generally speaking, the residual-scour stage, with a very low scour rate, has less effect on the soil resistance because the scour hole is already larger than the amplitude of pile movement after the main-scour stage.

If the drive speed is maintained at 60 RPM, the relatively large rod deflections will cause initially a relatively high rate of scour. Figure 5.19 shows the relationship between scour and duration of testing for cases where rod movements and frequency were kept constant. The time to reach the equilibrium stage for pile deflection larger than 1.6 mm is not shown by Fig. 5.19, but the scour processes for different rod deflections seem to be very similar. Although the quantity of scour still increased after one hour, the main scour was seen to be fully completed. The scour process may be faster for the smaller rod deflection at a constant frequency.

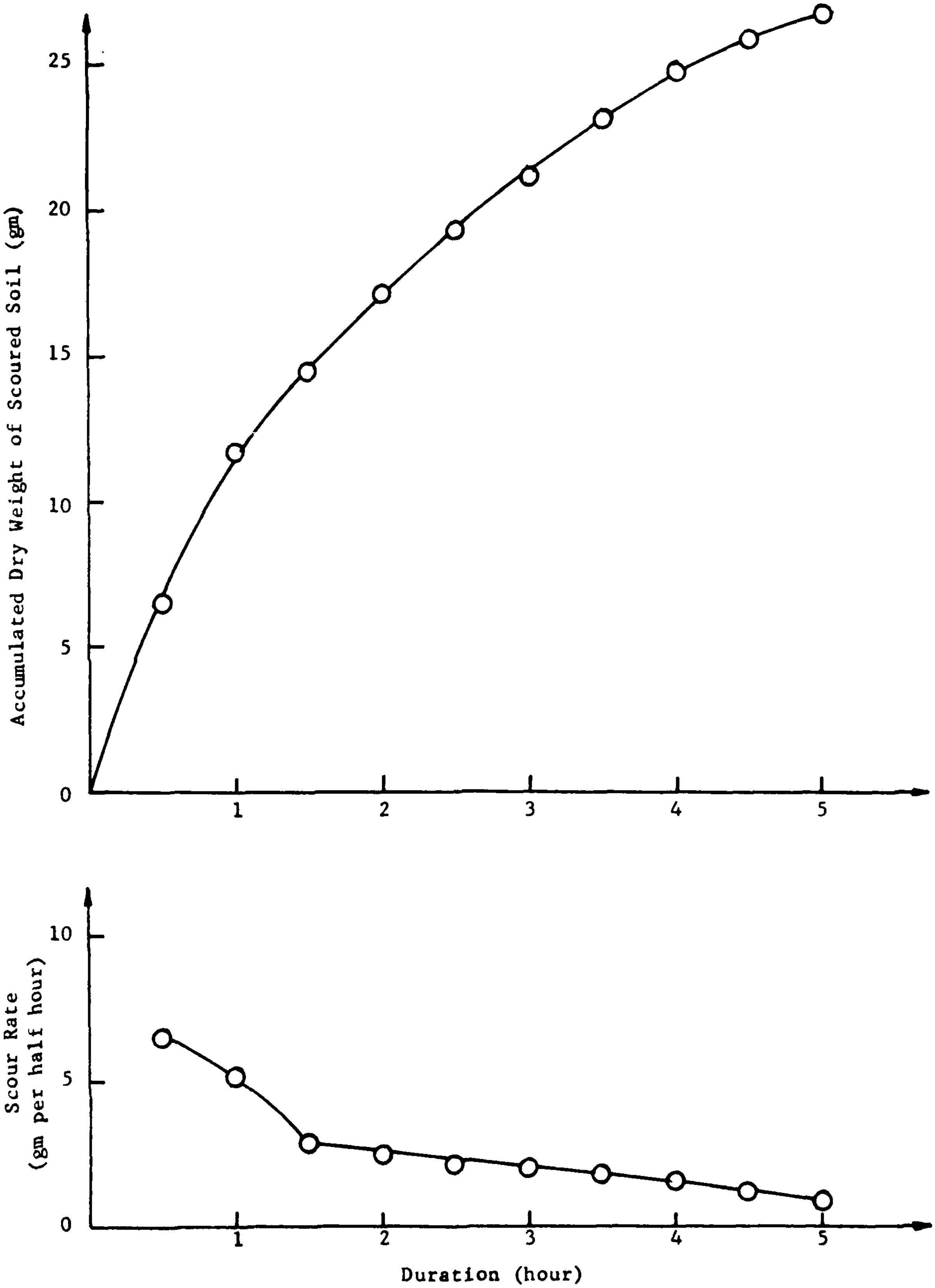


Fig. 5.18 Relationship between scour rate and duration of testing of Manor Clay under constant pile deflection (1.6 mm) and pile frequency (90 RPM)

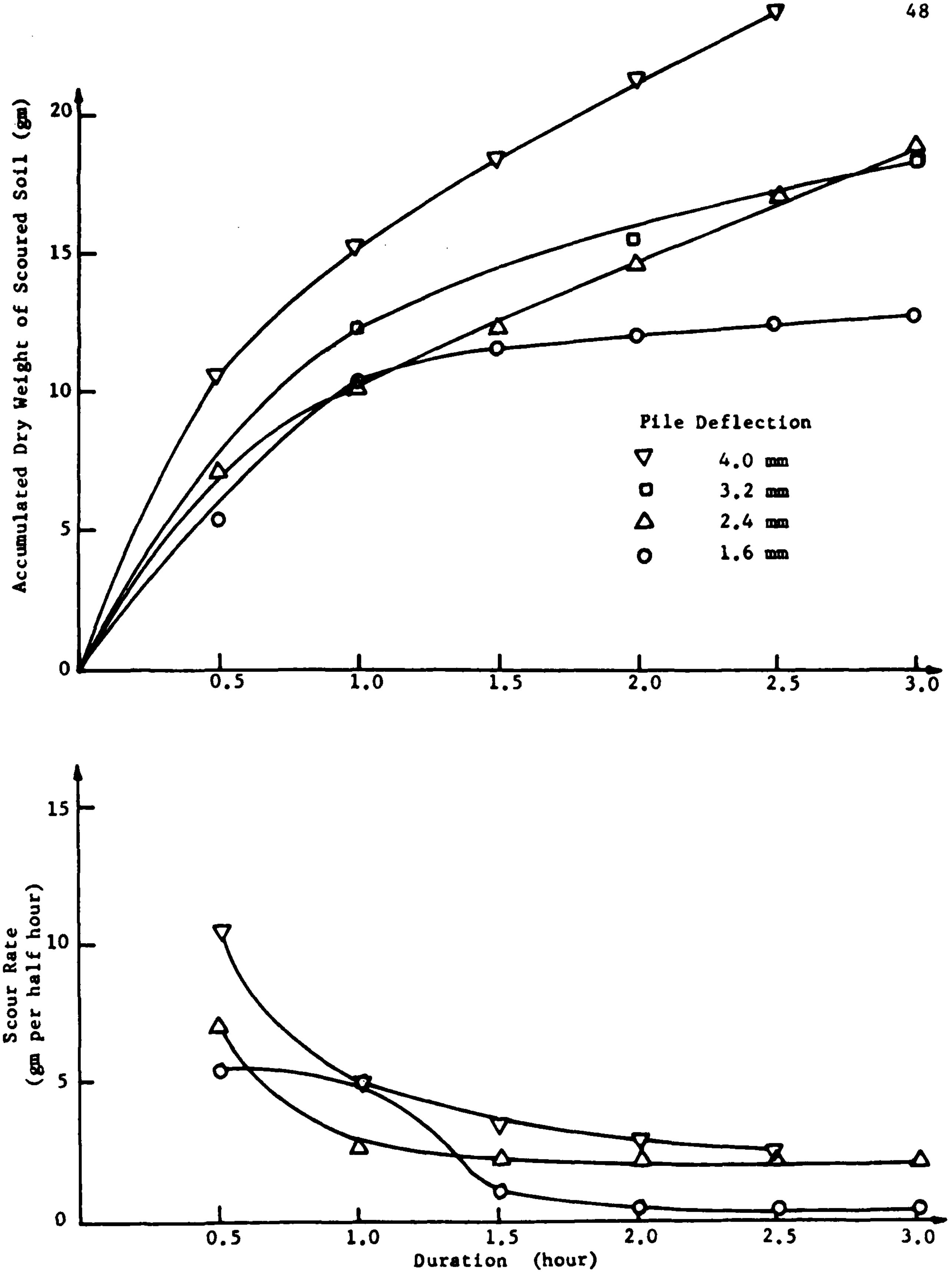


Fig. 5.19 Relationship between scour rate and duration of testing of Manor Clay under constant pile frequency (60 RPM)

5.4 COMPARISON OF RESULTS FROM PINHOLE TEST AND FROM PSSP TEST

In the last few years it has become more clearly understood that there are in nature certain dispersive clays[10] that are highly erodible. The fluid running through the dispersive clay carries a cloudy colored suspension of colloidal particles. The principal difference between dispersive clay and ordinary erosion-resistant clays is the nature of the cations in the pore water. Dispersive clays have a preponderance of sodium, whereas ordinary clays have a preponderance of calcium and magnesium cations in the pore water. The studies based on the pinhole test by Sherard[11] show that dispersive clays erode rapidly in the pinhole test. Conversely, essentially all the low sodium clays, previously designated as "ordinary, erosion-resistant clays", do not erode in the pinhole test. If the soil around the pile is dispersive clay, the scour resistance must be very low.

The pinhole test is not designed to be used as a quantitative test for measuring rate of scour as a function of the velocity of flow water, but it does serve as a good method of identifying dispersive clays.

Pinhole tests were performed on specimens SN-2 to SN-4 and the test data are presented in the Appendix. Comparisons between results from the pinhole test and the PSSP test are listed in Table 5.2. It can be established conclusively that dispersive clay is not a scour-resistant soil, but the high scour-potential soil found in the PSSP test may or may not be a dispersive clay.

TABLE 5.2 SUMMARY OF TEST RESULTS FROM PINHOLE TEST AND PSSP TEST

Test Sample	Classification of Soil	
	Pinhole Test	PSSP Test
SN-1 (fine sand)	--	Scour Resistant
SN-3 (silt)	Dispersive	Signiticant Scour Susceptibility
SN-2 (clayey silt)	Non-Dispersive	Intermediate Scour Susceptibility
SN-4 (Manor clay)	Non-Dispersive	Significant Scour Susceptibility

5.5 DATA INTERPRETATION

According to the study presented in this chapter, the weight loss in a given period of time is a function of the following variables:

C : soil properties (shear strength, unit weight, permeability, grain-size distribution, cations present).

N : number of cycles

v : fluid velocity

t : time

D : pile (rod) diameter

h : water head

d : cyclic deflection of pile (rod)

If the pile diameter and water head are held constant, these variables can be related by a simple equation of the form

$$S = \phi(C, N, v, t, d) \qquad (2)$$

where S = the dry weight of scoured soil. Because the fluid velocity is not easy to determine in the field, the frequency of loading can be used to relate the fluid velocity and the number of cycles. Then Eq. 2 can be written in the following form by assuming these variables are independent of each other

$$S = I \cdot f^m \cdot t^n \cdot d^p \qquad (3)$$

in which m, n, p are the exponents for frequency, time, and rod deflection; I is a proportionality constant related to the soil properties.

It is convenient to define I as the scour index of soil so that the relative scour for different samples can be compared. To determine the exponents in Eq. 3, the relations of log S versus log f, log S versus log t, and log S versus log d from Manor Clay were plotted on Figs. 5.20, 5.21 and 5.22, respectively, from which the exponents m, n, and p can be easily derived.

According to these analyses, initial values for the parameters in Eq. 3 have been determined:

$$S = I \cdot f^{0.6} \cdot t^{0.55} \cdot d^{0.6}$$

where f = loading frequency, cycles per minute

t = duration, hrs

d = rod deflection, mm

I = scour index of soil

S = dry weight of scoured soil, gm

The scour index I of remolded Manor clay computed from Eq. 3, based on experimental data, is about 0.56. Figures 5.23 and 5.24 show the comparisons of experimental curves and the curves calculated using these parameters and a reasonable fit is seen.

Furthermore, the scour indexes of the other soils were computed from Fig. 5.1. Table 5.3 presents a summary of the scour indexes determined for the various soils. The differences in the indexes are instructive in reflecting the relative susceptibility to scour of the four soils that were studied. Table 5.3 shows that the scour indexes for clays are significantly higher than that of the cohesionless soil. As mentioned in this

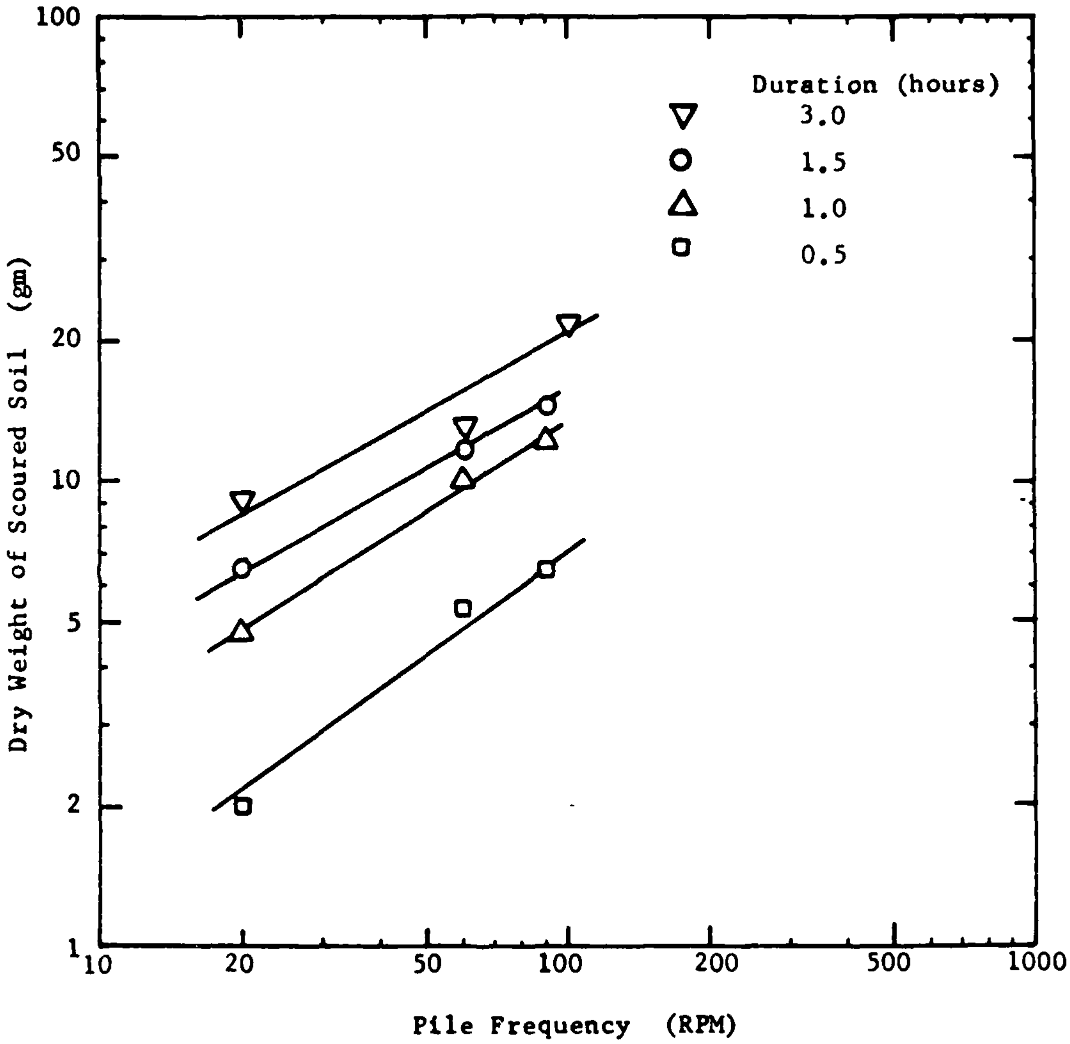


Fig. 5.20 Relationship of pile frequency and dry weight of scoured soil (Log Scale)

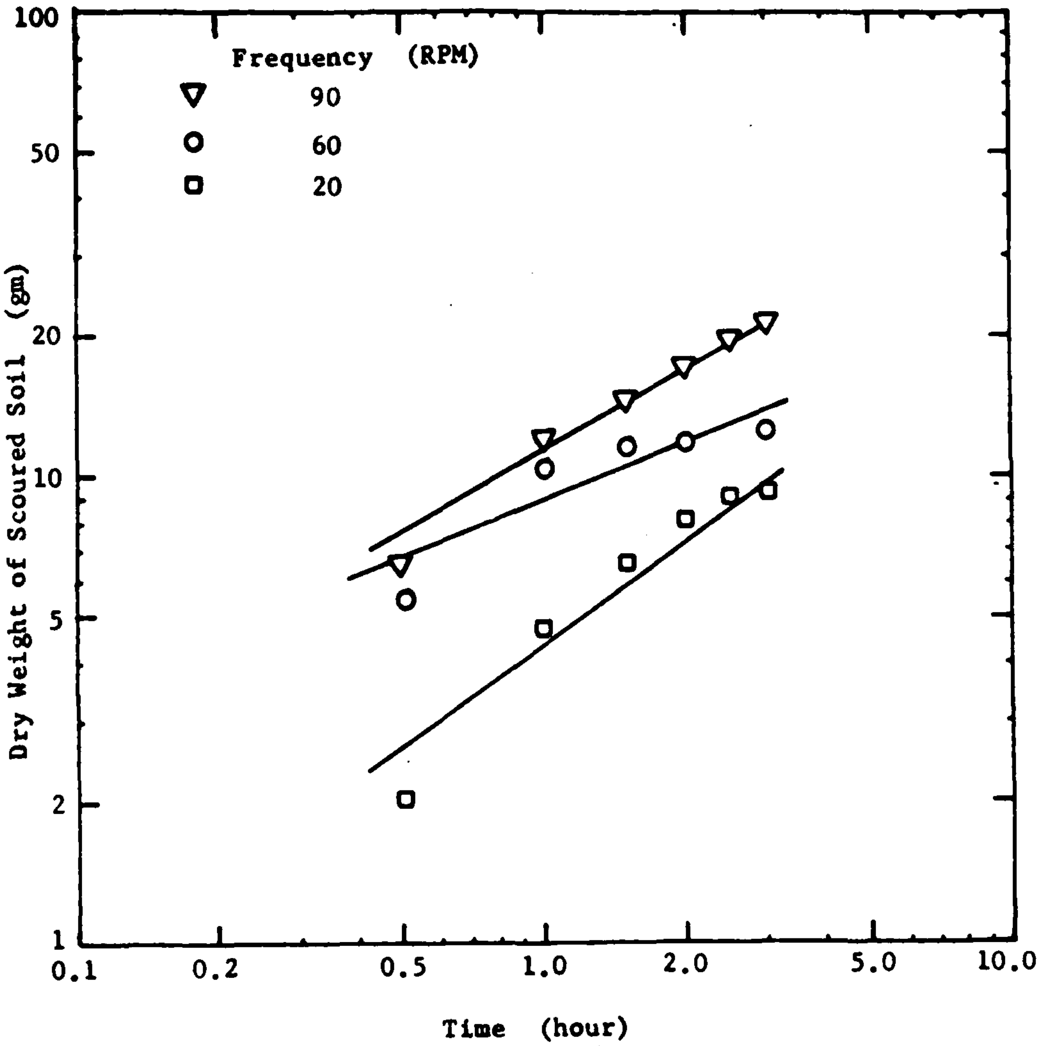


Fig. 5.21 Relationship of duration and dry weight of scoured soil (Log Scale)

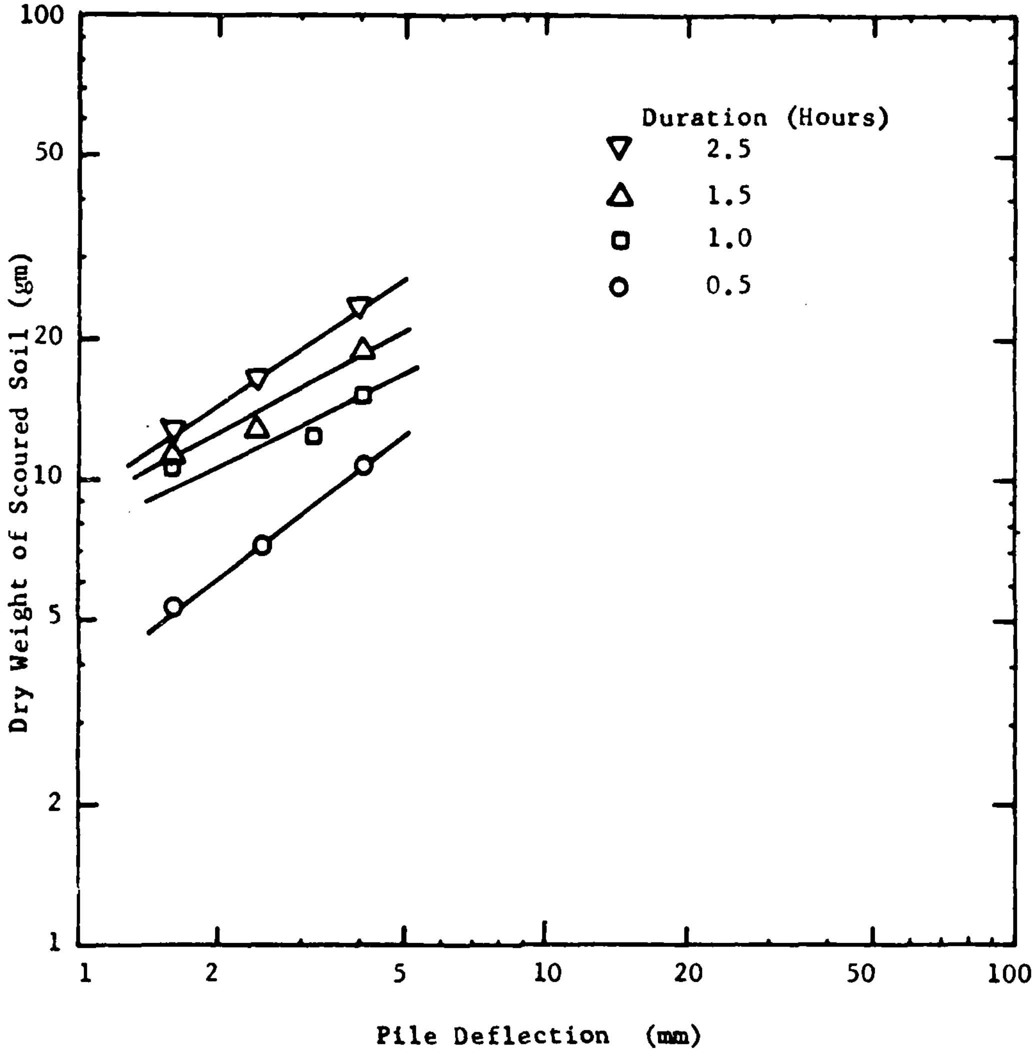


Fig. 5.22 Relationship of pile deflection and dry weight of scoured soil (Log Scale)

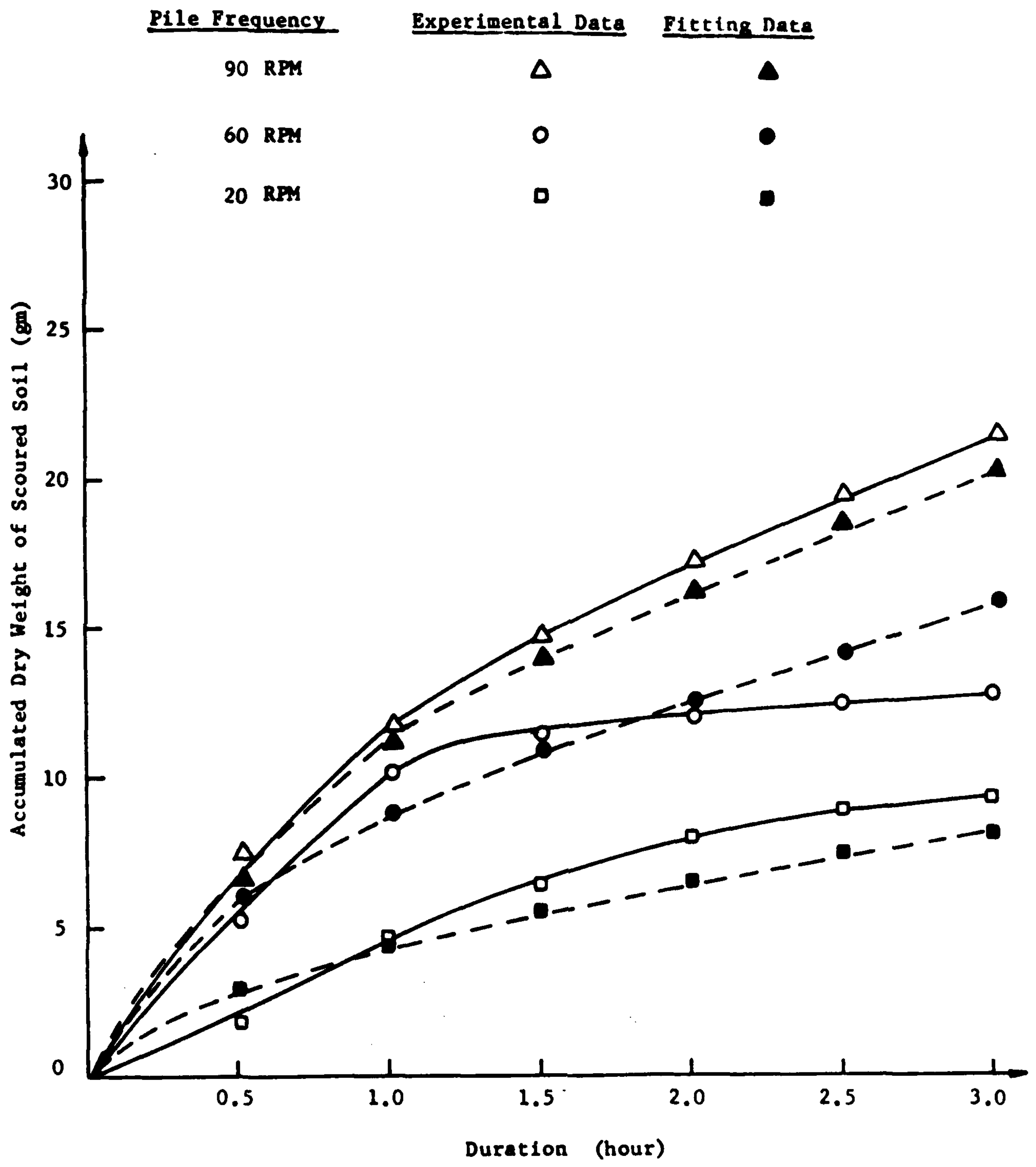


Fig. 5.23 Comparison of experimental data and fitting equation for Manor Clay at constant pile deflection (1.6 mm)

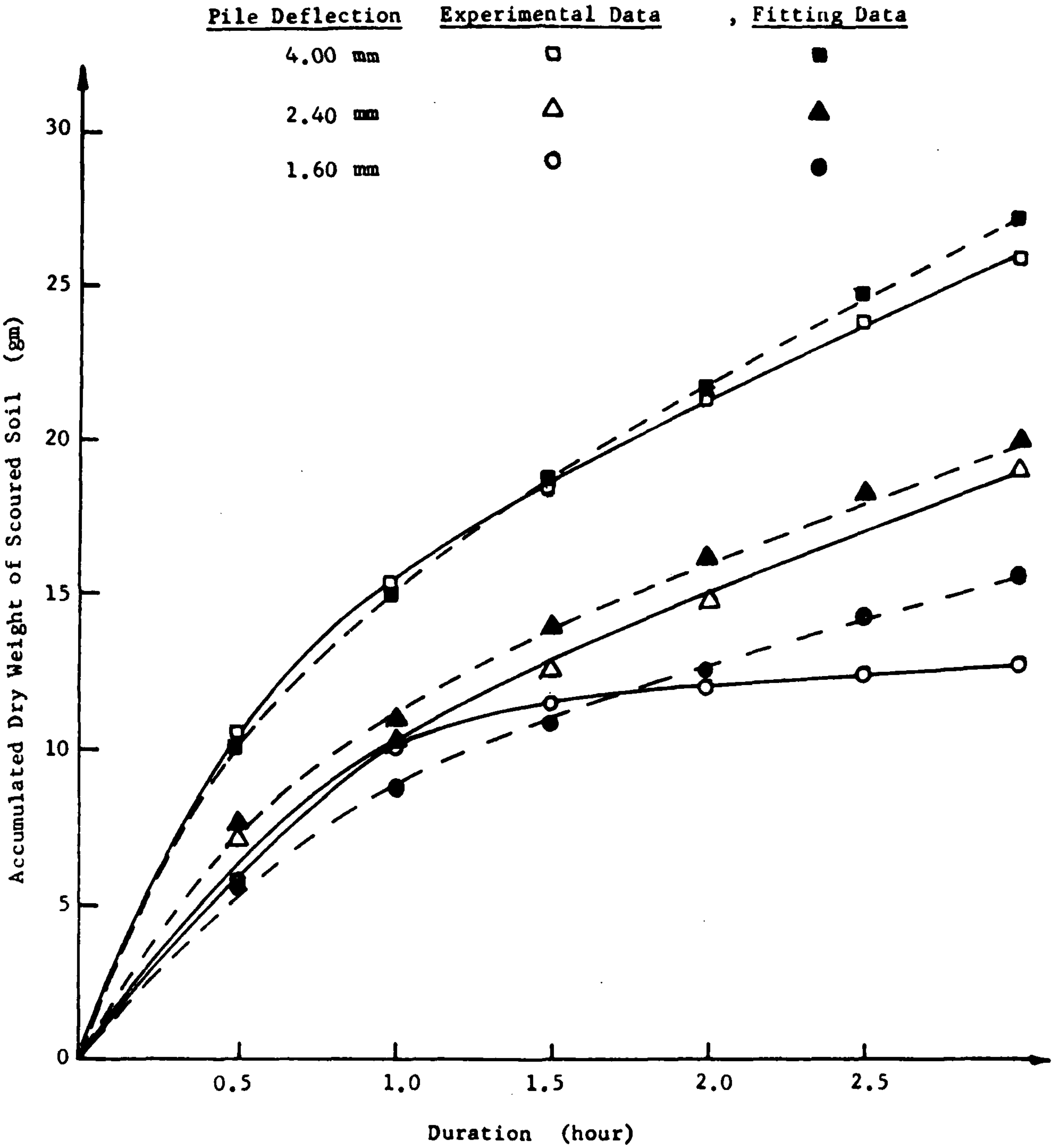


Fig. 5.24 Comparison of experimental data and fitting equation for Manor Clay at constant pile frequency (60 RPM)

TABLE 5.3 SUMMARY OF SCOUR INDEXES OF SAMPLES

Sample	Scour Index I
SN-1	0.06
SN-2	0.24
SN-3	0.40
SN-4	0.56

chapter the scour in the pile-soil interface occurred when the soil was molded away from a pile. Because the cohesionless sand was not involved in the "molding away", the sand will not be scoured like clays, but there are some fine particles in the sand that can be pumped out through the voids by the cyclic action of piles. Generally this quantity is too small to be counted.

CHAPTER 6. RESULTS FROM TESTING NATURAL SOILS

The study reported in Chapter 5 showed the natural soil to have a well-defined scour potential, and it was decided that it would be desirable to test other natural soils. The scour indexes determined from the PSSP test can possibly be of benefit to practicing engineers. Because 6-in.-diameter, undisturbed samples were not available, 3-in.-diameter, undisturbed samples were prepared for testing as described in Chapter 4.

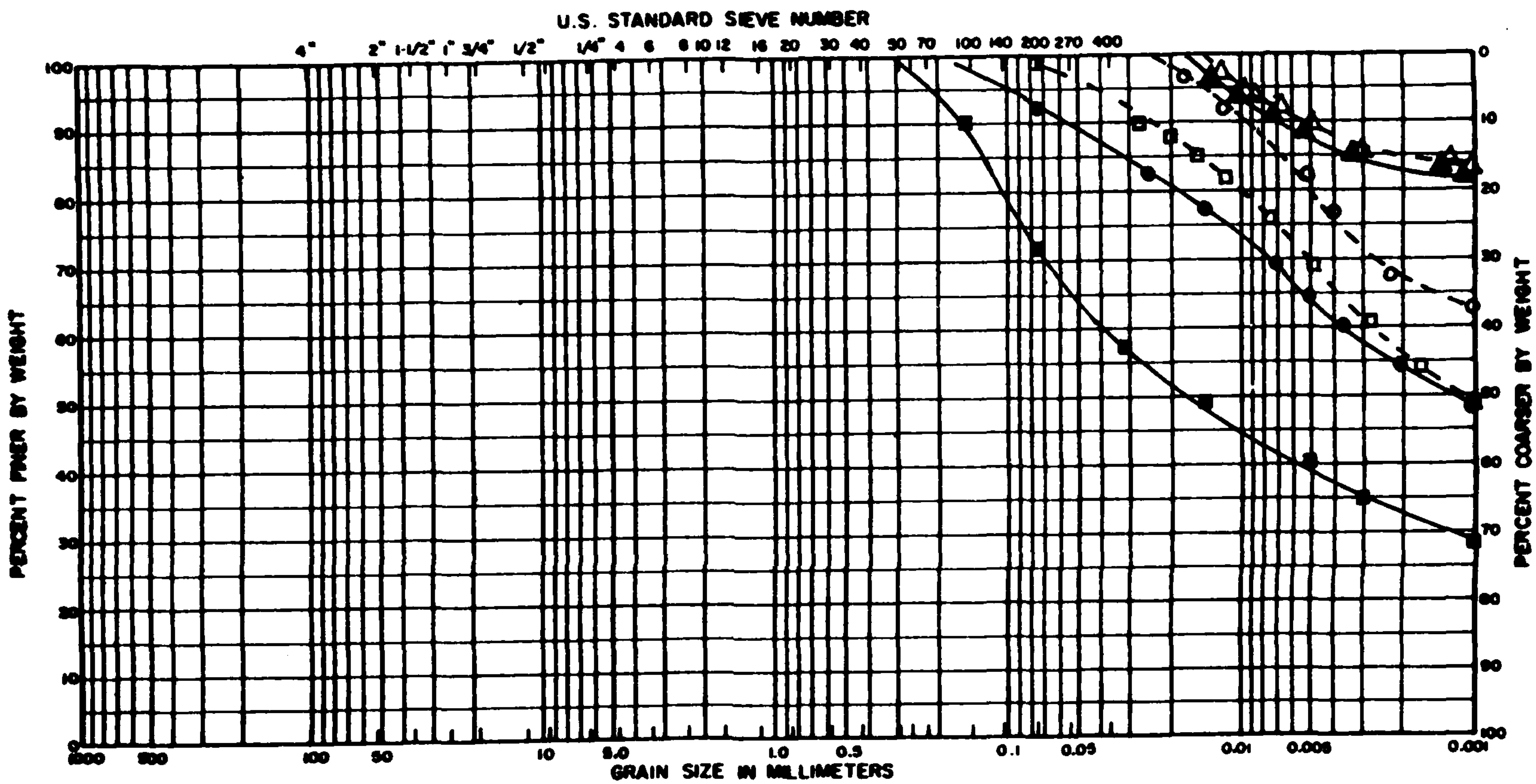
Undisturbed samples of Manor Clay, North Sea Clay, and Sabine Clay were available and their general characteristics are listed in Table 6.1. The Manor Clay has the highest plasticity index (PI) of the three and is classified as CH according to the Unified System, a clay with high plasticity. The Sabine Clay is just inside the CH range and probably should be classified as CL-CH, a clay with a medium plasticity. The Sabine Clay had the highest natural water content of the three and the lowest density (100 lb/ft^3). The North Sea Clay had a sand content of 28% and is classified as a low plasticity clay, a sandy or silty clay. Each of these samples consisted of fine grains and were thought, prior to testing, to be scour susceptible.

The gradation curves for the three soils are shown in Fig. 6.1.

The comparisons of scour potential between Manor Clay, North Sea Clay, and Sabine Clay are shown in Fig. 6.2. According to their scour indexes (about 0.27 to 0.48), they all have noticeable scour potential if compared with the values shown in Table 5.3. The variation as shown by upper-bound and lower-bound curves for each soil in Fig. 6.2 reflects the differences in

TABLE 6.1 SUMMARY OF SOIL PROPERTIES FOR MANOR, NORTH SEA, AND SABINE CLAY

Soil Type	Specific Gravity (Gs)	Particle Size Distribution (%)			Atterberg Limits			Natural Water Content W (%)
		Sand	Silt	Clay	LL	pL	PI	
Manor Clay	2.74	0	15	85	80	27	53	30
Sabine Clay	2.70	9	33	58	51	17	34	65
North Sea Clay	2.70	28	39	33	30	14	16	20



■ Sample from North Sea Clay

□ Sample from the Scoured Soil of North Sea Clay

● Sample from Sabine Clay

○ Sample from the Scoured Sabine Clay

▲ Sample from Manor Clay

△ Sample from the Scoured Manor Clay

Fig. 6.1 Gradation curves of natural soils

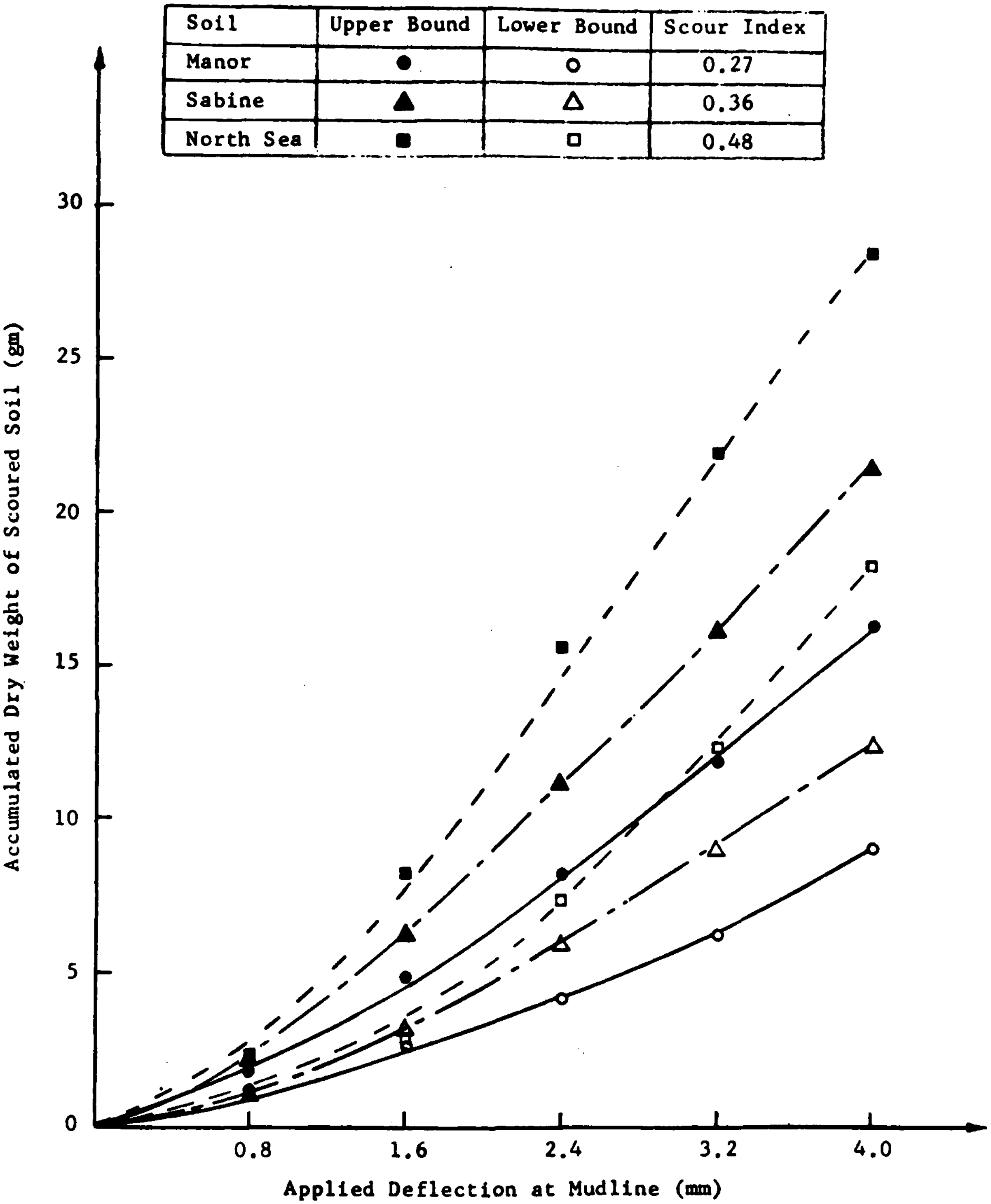


Fig. 6.2 Comparison of scour resistance of Manor Clay, North Sea Clay, and Sabine Clay

the natural soils (samples from different depths were tested) and the scour index was taken average between the curves. It is apparent that the scour potential of the North Sea Clay is significantly higher than the others. There are many unknowns about the influence of soil properties on scour resistance, but generally the higher PI value will mean a higher cohesive strength. Sands do not exhibit much scour because water can flow through the pore spaces. Clays with a greater cohesive strength should be more scour resistant than those with lesser cohesive strength. Because all these samples are cohesive fine soil (Fig. 6.1), the lower plasticity of North Sea Clay could be the principal explanation for its higher scour potential.

The general characteristics of scour can be seen from the comparisons in Fig. 6.2 for Manor Clay, North Sea Clay, and Sabine Clay. The scour indexes do serve as a good indication of the results of the tests. However, further studies are necessary before the scour index can be integrated in the design process for offshore structures.

CHAPTER 7. RECOMMENDATIONS

For the present, it is recommended that the PSSP test be employed in the laboratory to investigate the scour potential of various soils.

With regard to details, it is recommended that the following procedures be adopted.

1. The test arrangement should be as shown in Figs. 4.1 and 4.2 with the soil mold having a diameter of 6-in. (15.2 cm) and a height of 7-in. (17.8 cm).

2. The rod used should be steel pipe with 14-in. (35.6 cm) length and 3/4-in. (1.9 cm) diameter and hinged at the bottom of the mold.

3. The frequency of load application should be 60 RPM.

4. The initial deflection at the surface of the sample should be 1/32-in. (0.8 mm) and subsequent deflections should be in increments of 1/32-in. (0.8 mm).

5. The duration should be 1 hour for each deflection and the scoured soil collected every one hour.

6. The test is to be continued until the applied deflection reaches 5/32-in. (4.0 mm). The dry weight of the scoured soil is accumulated for use in comparing the relative scour potential of various soils.

CHAPTER 8. SUMMARY AND CONCLUSIONS

This report presents a study of the scour potential around the pile-soil interface. A laboratory test (PSSP test) was developed and studied thoroughly. The PSSP test was successfully applied to evaluate the scour potential of several soils.

From an engineering standpoint, the aim of this investigation was to provide a means by which an engineer can make reliable estimates of the scour potential of various soils. If additional data become available in time, it may be possible to use the scour index obtained by the PSSP test in making quantitative predictions of p-y curves. The complexity of the total problem eliminates a simple and quick solution. A satisfactory answer may require the measurement of scour-resistance properties of a soil, the variation of shear strength with time, patterns of fluid flow around the pile-soil interface, depth of scour opening, and the reduction of soil resistance on the pile. All of these problems are worthy of further investigation in order to get a reliable evaluation of scour potential.

The following conclusions were drawn from the experimental study of scour around the interface of marine piling:

1. The particle size is an important factor in scour resistance. Non-plastic, coarse to fine sand seems to be a scour resistant soil. Cohesive soil with finer particles is more susceptible to scour.

2. The scour is affected by a variation of soil properties. The compacted Manor Clay shows higher scour potential than the undisturbed Manor

Clay. The North Sea clay was more susceptible to scour than natural soils with a higher clay content.

3. The speed of rod movement has a significant influence on scour. The soil seems to be less scour resistant at higher frequencies of loading.

4. The dispersive clay defined by the pinhole test is not a scour resistant soil, but the high-scour-potential soil found in the PSSP test may or may not be a dispersive clay.

5. The equilibrium stage of scour is defined as that at which little or no scour is occurring with increased cycles of deflection. The scour process will reach the equilibrium stage finally if the cyclic deflection of pile is held constant by underlying layers. The time to reach the equilibrium stage varies with the boundary conditions.

6. Using the scour index from the PSSP test seems to be a feasible method for the evaluation of sour potential and is worthy of further study.

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APPENDIX

Pinhole Test Data

PINHOLE TEST DATA

Pinhole Test No. 1

Date: May 30, 1982

Sample No. SN - 3

Page: 1

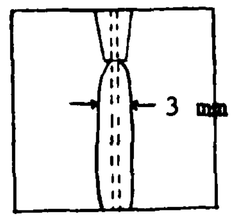
Compaction Characteristics γ_d =106 lb/ft^3

Water Content 29.4%

Distilled Water Added: V (Yes) or ____ (No)

Curing Time: 4 hours

Specimen After Test:



Flow Started On 1st Trial.

Clock Time	Head	Flow Rate		Color From Side				Completely Clear	Particles Falling			Remarks
8:00pm	in.	ml	sec	Dark	Slight To Medium	Barely Visible	Completely Clear		None	Few	Heavy	
45'30"	2	100	76	V					V			
47'30"	2	100	72	V					V			
51'30"	2	100	73	V					V			
55'30"	2	100	73		V					V		
58'30"	2	100	74		V					V		
(9:00) 02'30"	2	100	76		V					V		Stop Test

PINHOLE TEST DATA

Pinhole Test No. 2

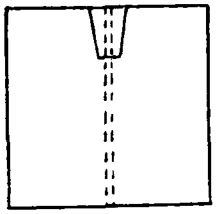
Date: June 1, 1982

Sample No. SN - 4

Page: 1

Compaction Characteristics γ_d =94.8 lb/ft^3

Specimen After Test:



Water Content 34.6%

Distilled Water Added: V (Yes) or ____ (No)

Curing Time: 4 hours

Flow Started On 1st Trial.

Clock Time 1:00 pm	Head in.	Flow Rate ml	Flow Rate sec	Color From Side: Dark	Color From Side: Slight To Medium	Color From Side: Barely Visible	Color From Side: Completely Clear	Completely Clear	Particles Falling: None	Particles Falling: Few	Particles Falling: Heavy	Remarks
40'00"	2	100	87			V			V			
42'00"	2	100	90				V	V	V			
44'00"	2	100	88				V	V	V			
47'00"	2	100	87				V	V	V			
51'00"	7	100	49				V	V	V			
53'00"	7	100	56				V	V	V			
55'00"	7	100	54				V	V	V			
57'00"	7	100	54				V	V	V			

PINHOLE TEST DATA

Pinhole Test No. 2

Date: June 1, 1982

Sample No. SN - 4

Page: 2

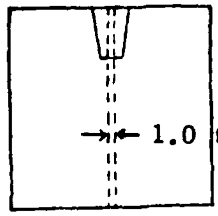
Compaction Characteristics γ_d =94.8 lb/ft^3

Water Content 34.6%

Distilled Water Added: V (Yes) or ____ (No)

Curing Time: 4 hours

Specimen After Test:



Flow Started On 1st Trial.

Clock Time	Head	Flow Rate		Color From Side					Particles Falling			Remarks
2:00pm	in.	ml	sec	Dark	Slight To Medium	Barely Visible	Completely Clear	Completely Clear	None	Few	Heavy	
02'00"	15	100	44				V	V	V			
04'00"	15	100	44				V	V	V			
06'00"	15	100	43				V	V	V			
08'00"	15	100	45				V	V	V			
12'00"	40	100	34				V	V	V			
14'00"	40	100	35				V	V	V			
16'00"	40	100	35				V	V	V			
18'00"	40	100	34				V	V	V			Stop Test

PINHOLE TEST DATA

Pinhole Test No. 3 Date: June 2, 1982

Sample No. SN - 4 Page: 2

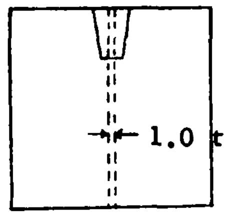
Compaction Characteristics γ_d =98.7 lb/ft^3

Water Content 23%

Distilled Water Added: v (Yes) or ___ (No)

Curing Time: 1 day

Specimen After Test:



1.0 to 1.5 mm

Flow Started On 1st Trial.

Clock Time 3:00pm	Head in.	Flow Rate ml	Flow Rate sec	Color From Side: Dark	Color From Side: Slight To Medium	Color From Side: Barely Visible	Color From Side: Completely Clear	Completely Clear	Particles Falling: None	Particles Falling: Few	Particles Falling: Heavy	Remarks
47'00"	40	900	197			V			V			
53'00"	40	900	196				V	V	V			
(4:00pm) 01'00"	40	1000	252				V	V	V			
08'00"	40	1000	254				V	V	V			
25'00"	40	1000	264				V	V	V			
35'00"	40	1000	257				V	V	V			
50'00"	40	1000	278				V	V	V			
58'00"	40	1000	276				V	V	V			Stop Test

PINHOLE TEST DATA

Pinhole Test No. 4

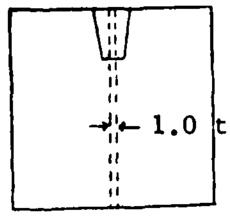
Date: June 5, 1982

Sample No. SN - 2

Page: 2

Compaction Characteristics γ_d =105 lb/ft^3

Specimen After Test:



Water Content 19.2%

Distilled Water Added: V (Yes) or ___ (No)

Curing Time: 12 Hours

Flow Started On _____ Trial.

Clock Time	Head	Flow Rate		Color From Side				Completely Clear	Particles Falling			Remarks
2:00pm	in.	ml	sec	Dark	Slight To Medium	Barely Visible	Completely Clear		None	Few	Heavy	
08'00"	40	900	210			V			V			
16'00"	40	900	210				V	V	V			
30'00"	40	900	215				V	V	V			
(4:000m) 25'00"	40	900	220				V	V	V			
(5:00pm) 00'30"	40	900	218				V	V	V			Stop Test

END
DATE
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